National Aeronautics and Space Administration



5 . . . 4 . . . 3 . . . 2 . . . 1 . . .

SPACE LAUNCH SYSTEM

NASA Langley Low-Speed CFD Contributions to the Space Launch System Program

Brent Pomeroy

Steve Krist, TJ Wignall, Michael Lee, Farhad Ghaffari, Karen Deere, Jeremy Pinier
NASA Langley, Configuration Aerodynamics Branch

Craig Streett
NASA Langley, Computational Aerosciences Branch

Advanced Modeling & Simulation (AMS) Seminar Seri
NASA Ames Research Center, May 19th, 2022
https://www.nas.nasa.gov/pubs/ams.html

This material is a work of the U.S. Government and is not subject to copyright protection in the United States

www.nasa.gov/sls

OUTLINE

- Introduction and Overview
- Methods
- Liftoff and Transition Above Tower
- Liftoff and Transition in Proximity of Tower
- Other Program Requests



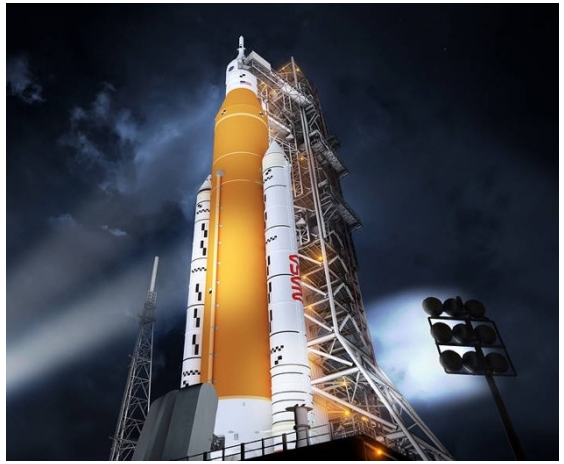
OUTLINE

- **Introduction and Overview**
  - The Team
  - Mission Profile
  - Program Deliverables
  - High-Alpha, Slender-Body Aerodynamics
- **Methods**
- **Liftoff and Transition Above Tower**
- **Liftoff and Transition in Proximity of Tower**
- **Other Program Requests**



LANGLEY SLS CFD TEAM

- **Large, diversified team**
  - Brent Pomeroy, CFD Team Lead
  - Steve Krist, Subject Matter Expert
  - TJ Wignall
  - Michael Lee
  - Farhad Ghaffari
  - Karen Deere
  - Craig Streett
  - Jeremy Pinier, Langley Aerodynamics Lead, Agency Aerosciences Lead for Technical Quality
  - Previous members (including many interns)
- **Key efforts**
  - Dedicated to low-speed regime
  - High-fidelity DDES simulations
  - Reduced-order modeling
  - Technology development

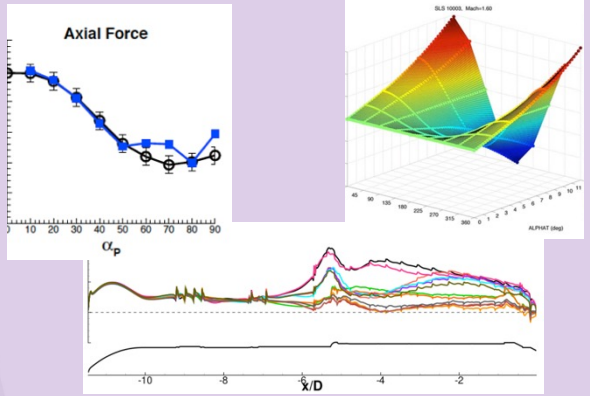




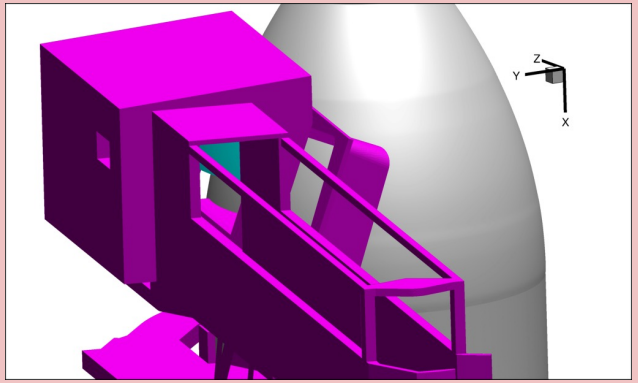


COMPUTATIONAL EFFORTS TO SLS AT LANGLEY

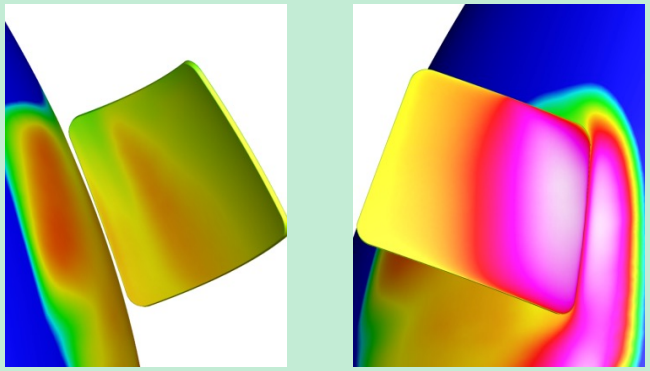
Databases



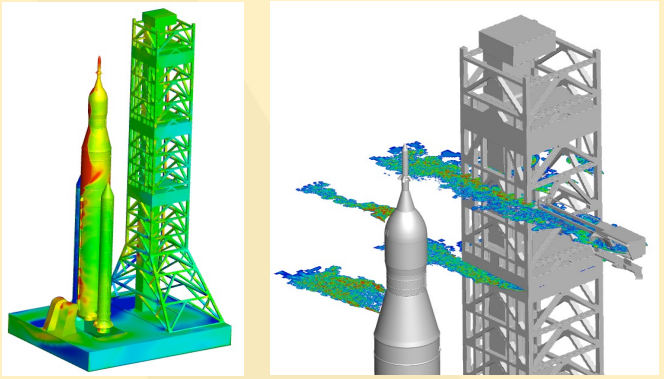
Crew Access Arm



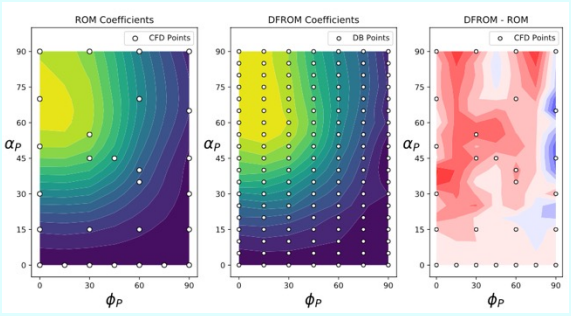
Launch Abort System Hatch



Launch Pad Tower Effects

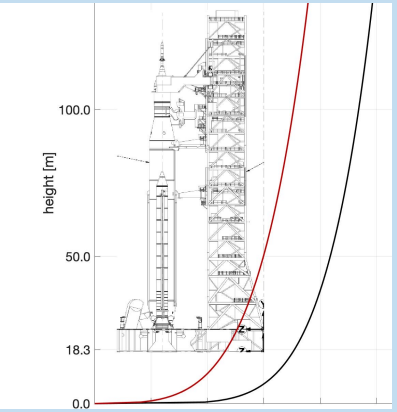


Reduced Order Modeling



$$\frac{\partial L}{\partial \lambda_j} = \lambda_j \sum_{i=1}^{npc} \sum_{l=1}^{nvar} \hat{a}_i^l \Delta c_{i,j}^l - C_{F_j}$$

Atmospheric Boundary Layer



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport

1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center

2 JETTISON ROCKET BOOSTERS
Solid rocket boosters separate

3 JETTISON LAUNCH ABORT SYSTEM (LAS)
The LAS is no longer needed, Orion could safely abort

4 CORE STAGE MAIN ENGINE CUT OFF (MECO) and separation

5 ENTER EARTH ORBIT
Perform the perigee raise maneuver

6 EARTH ORBIT
Systems check and solar panel adjustments

7 TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes

8 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION
The ICPS has committed Orion to TLI

9 OUTBOUND TRANSIT
Requires several attitude maneuvers

A B C D
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

10 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for Lunar flyby to DRO

11 OUTBOUND POWERED FLYBY (OPF)
62 miles from the Moon; targets DRO insertion

Heliocentric Disposal precludes re-contact

12 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-23 days

13 DISTANT RETROGRADE ORBIT (DRO)
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon

14 DRO DEPARTURE
Leave DRO and start return to Earth

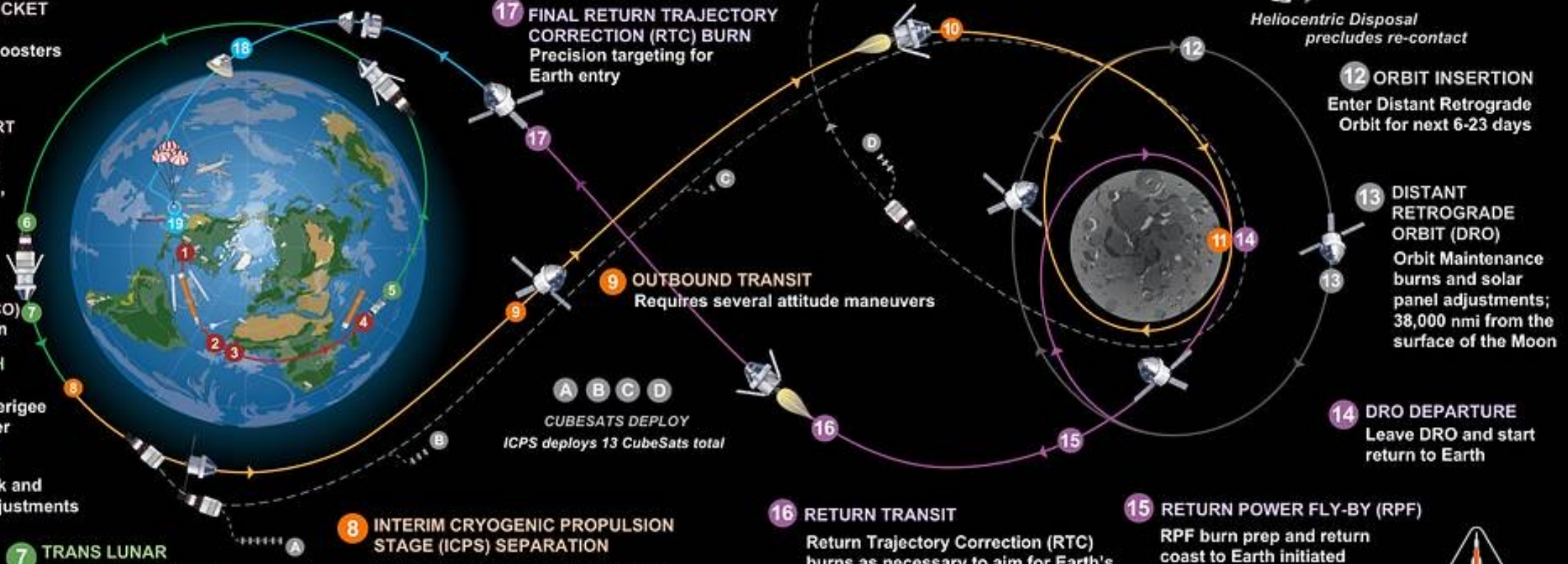
15 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated

16 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days

17 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry

18 ENTRY INTERFACE (EI)
Enter Earth's atmosphere

19 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships



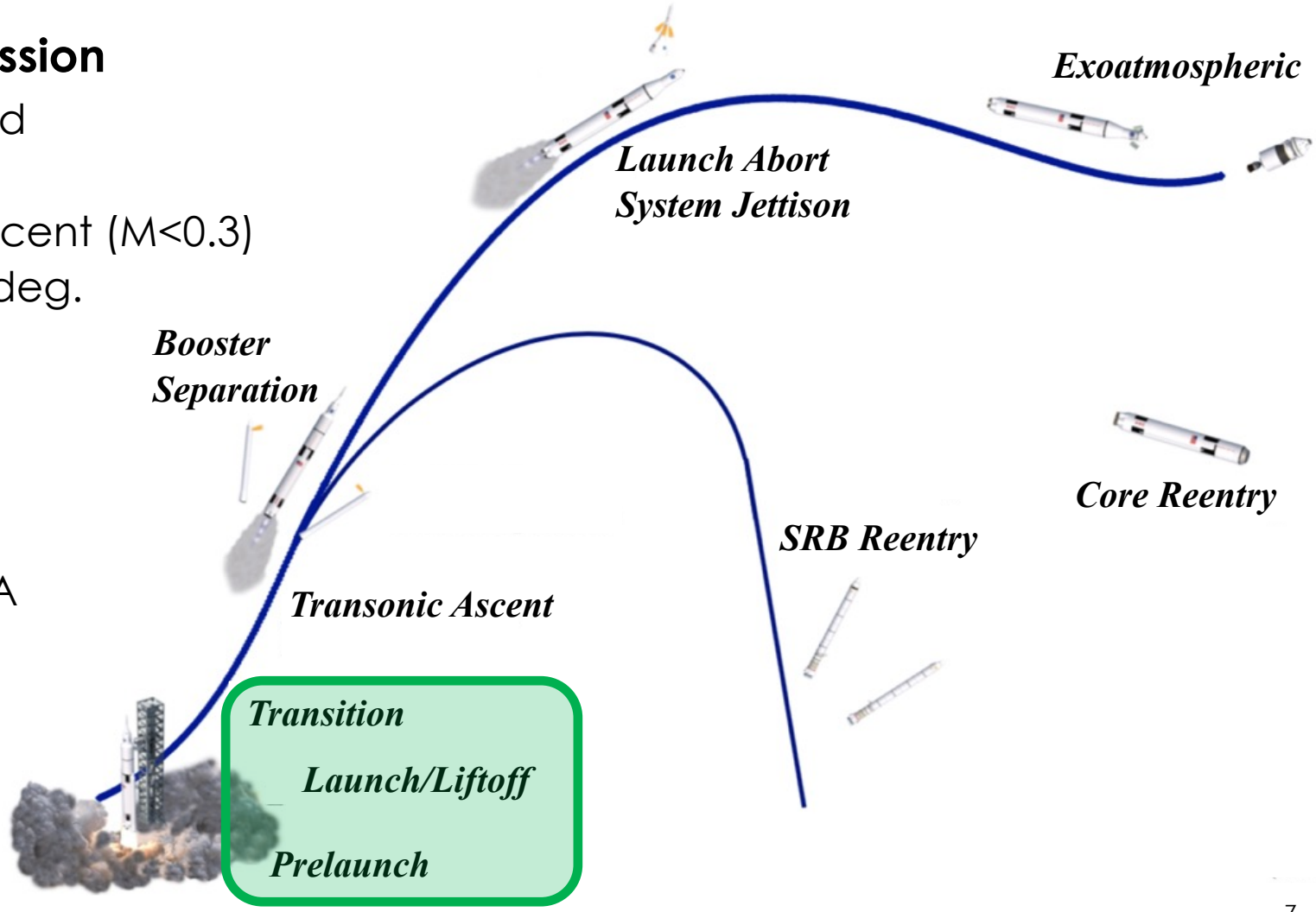
ARTEMIS

ARTEMIS I

Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

SLS MISSION PROFILE

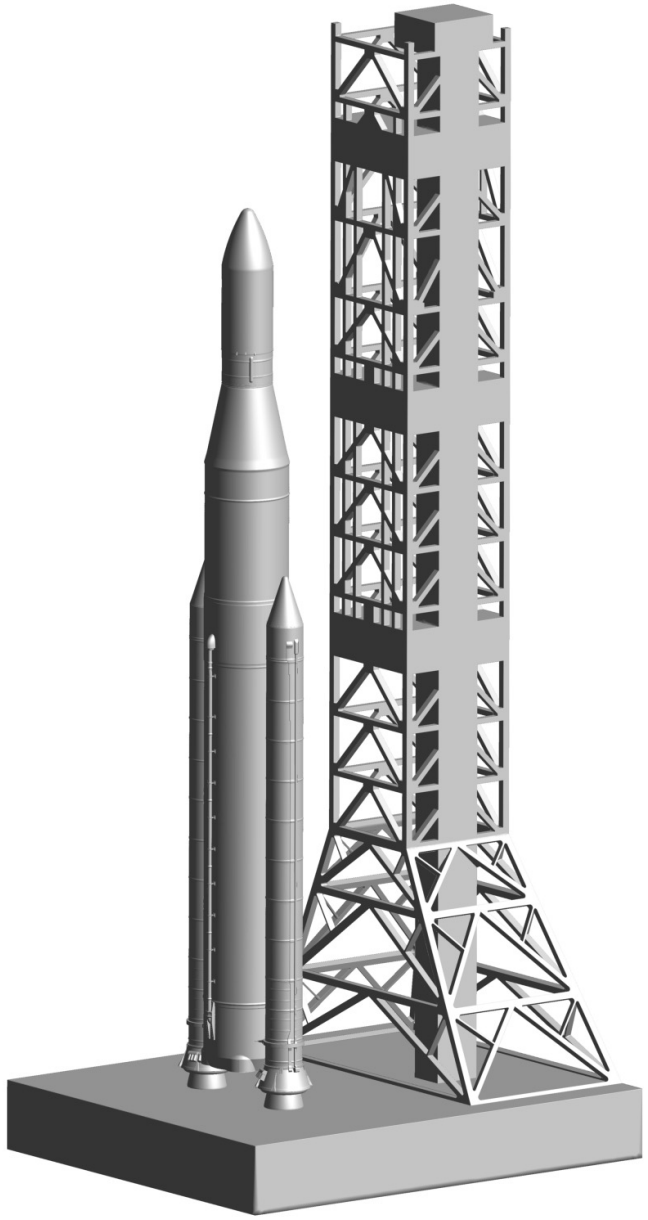
- **Flight regimes range from low speed to supersonic**
- **Langley CFD efforts focused on the early portions of the mission**
  - Rocket static on the launch pad
  - In proximity of the tower
  - Above the tower but before ascent (M<0.3)
  - Angle of attack (AOA) 0 to 90 deg.
  - Includes first ~20 sec. of flight
- **Complex aerodynamics**
  - Asymmetric vortices at mid-range AOA
  - Massive flow separation at AOA above 20 deg.



LOW-SPEED FLIGHT REGIME

- **Prelaunch**
  - Begins when vehicle exits the Vehicle Assembly Building
  - Can last for numerous weeks

- **Liftoff and Transition Near Tower**
  - Vehicle stationed on launch pad
  - Tower effects are significant
  - Freestream alpha 90 deg. (α_P)
  - Roll angle 0 to 360 deg. (ϕ_P)
- **Liftoff and Transition in Isolation**
  - Begins after rocket clears the tower and ends at Mach 0.3
  - Centered on the isolated vehicle
  - Angle of attack from 90 to 0 deg. (α_P)
  - Roll angle 0 to 360 deg. (ϕ_P)



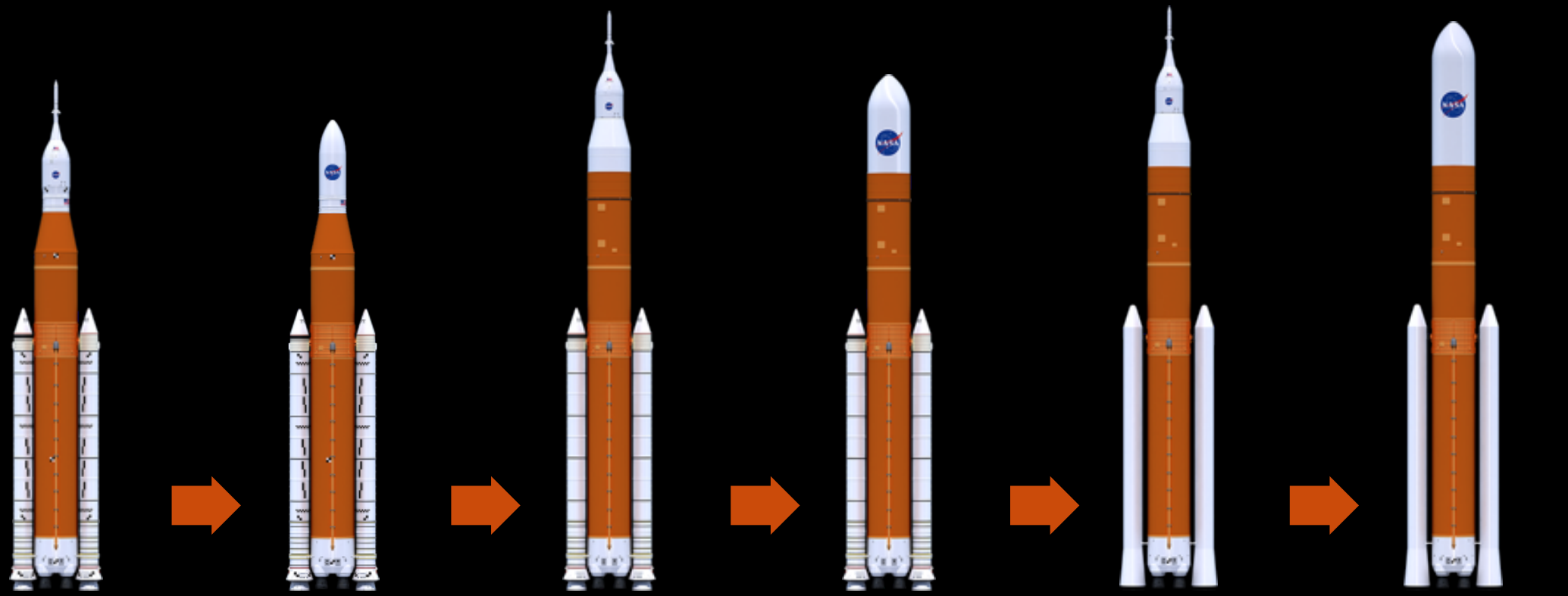
SLS FAMILY OF VEHICLES

	SLS Block 1 Crew	SLS Block 1 Cargo	SLS Block 1B Crew	SLS Block 1B Cargo	SLS Block 2 Crew	SLS Block 2 Cargo
Payload to LEO	95 t (209k lbs)	95 t (209k lbs)	105 t (231k lbs)	105 t (231k lbs)	130 t (287k lbs)	130 t (287k lbs)
Payload to TLI/Moon	> 26 t (57k lbs)	> 26 t (57k lbs)	34–37 t (74k–81k lbs)	37–40 t (81k–88k lbs)	> 45 t (99k lbs)	> 45 t (99k lbs)
Payload Volume	N/A**	9,030 ft^3 (256m^3)	10,100 ft^3 (286m^3)**	18,970 ft^3 (537 m^3)	10,100 ft^3 (286m^3)**	34,910 ft^3 (988 m^3)

Low Earth Orbit (LEO) represents a typical 200 km circular orbit at 28.5 degrees inclination

Trans-Lunar Injection (TLI) is a propulsive maneuver used to set a spacecraft on a trajectory that will cause it to arrive at the Moon. A spacecraft performs **TLI** to begin a lunar transfer from a low circular parking orbit around Earth.

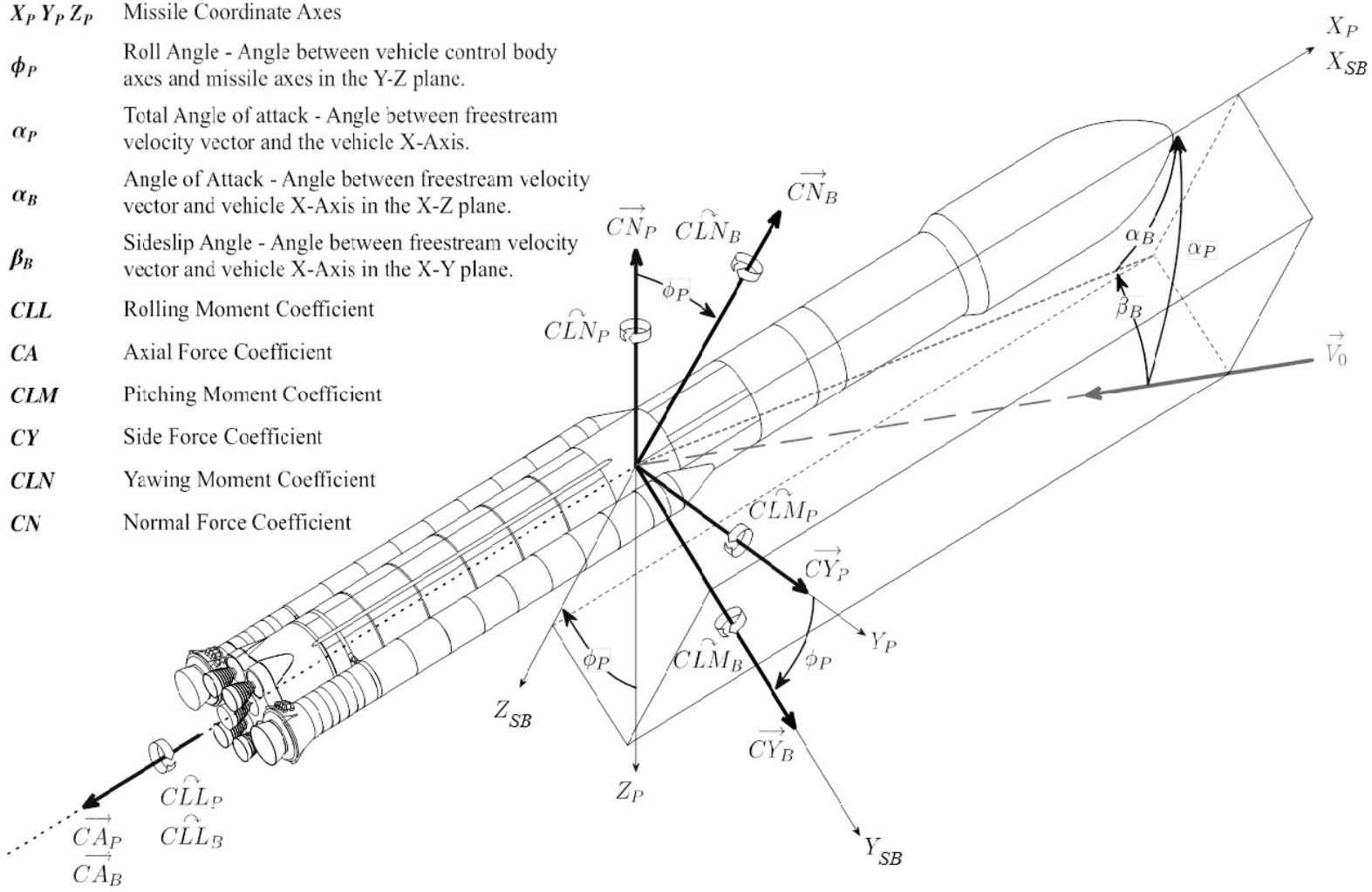
The numbers depicted here indicate the mass capability at the Trans-Lunar Injection point.



	SLS Block 1 Crew	SLS Block 1 Cargo	SLS Block 1B Crew	SLS Block 1B Cargo	SLS Block 2 Crew	SLS Block 2 Cargo
Maximum Thrust	8.8M lbs	8.8M lbs	8.8M lbs	8.8M lbs	11.9M lbs	11.9M lbs

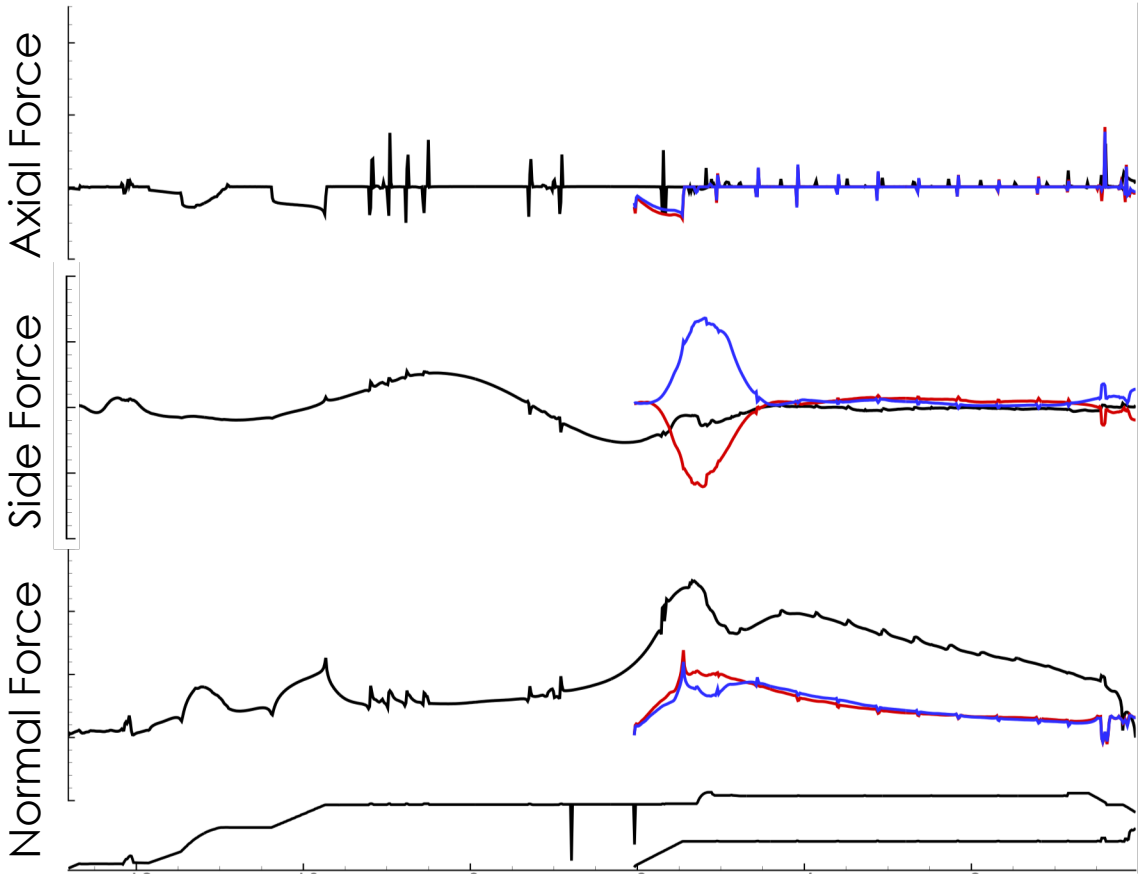
MISSILE AXIS COORDINATE SYSTEM

V_0	Freestream Flow Velocity Vector
$X_{SB}\ Y_{SB}\ Z_{SB}$	Control Body Coordinate Axes
$X_P\ Y_P\ Z_P$	Missile Coordinate Axes
ϕ_P	Roll Angle - Angle between vehicle control body axes and missile axes in the Y-Z plane.
α_P	Total Angle of attack - Angle between freestream velocity vector and the vehicle X-Axis.
α_B	Angle of Attack - Angle between freestream velocity vector and vehicle X-Axis in the X-Z plane.
β_B	Sideslip Angle - Angle between freestream velocity vector and vehicle X-Axis in the X-Y plane.
CLL	Rolling Moment Coefficient
CA	Axial Force Coefficient
CLM	Pitching Moment Coefficient
CY	Side Force Coefficient
CLN	Yawing Moment Coefficient
CN	Normal Force Coefficient



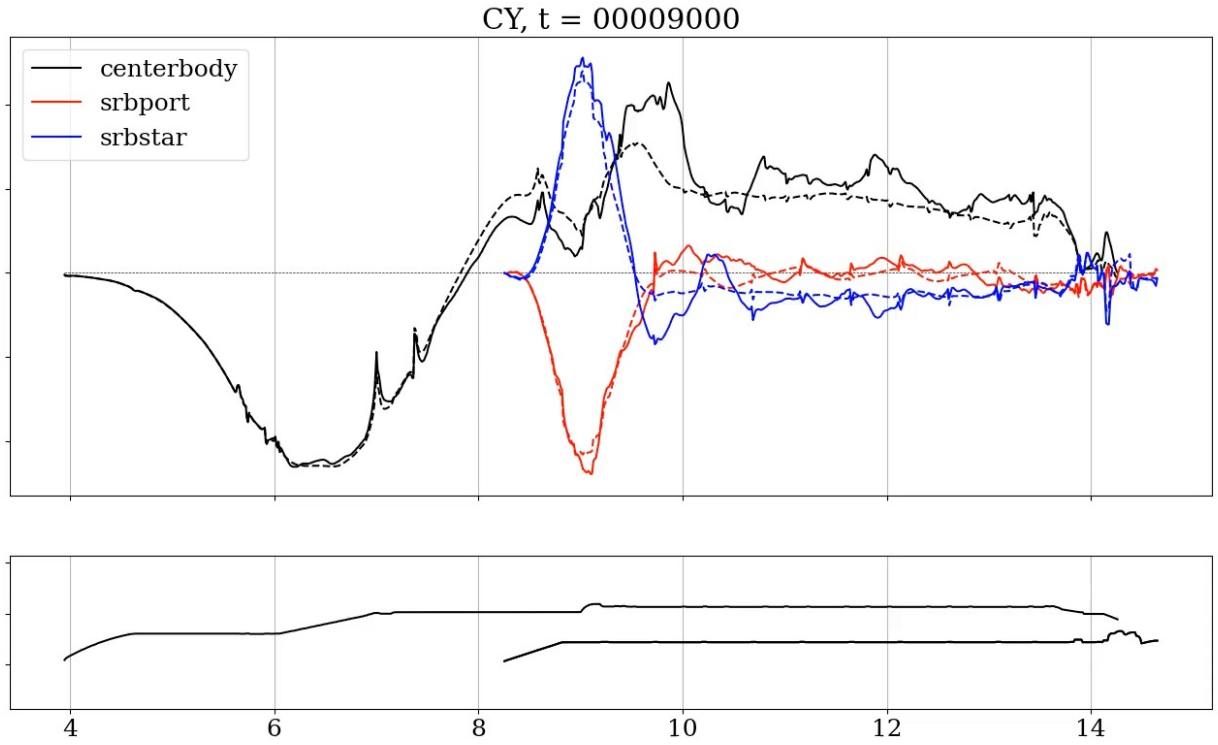
SIGNIFICANT PROGRAM DELIVERABLES

- **Information primarily used by Loads and Guidance, Navigation, & Control**
- **Force and moment databases**
  - Full-vehicle F&M
  - Component breakdown
- **Lineloads**
  - Achievable only through CFD
  - Longitudinal load distribution in all three axes
  - Includes both pressure and skin friction components



LINELOADS

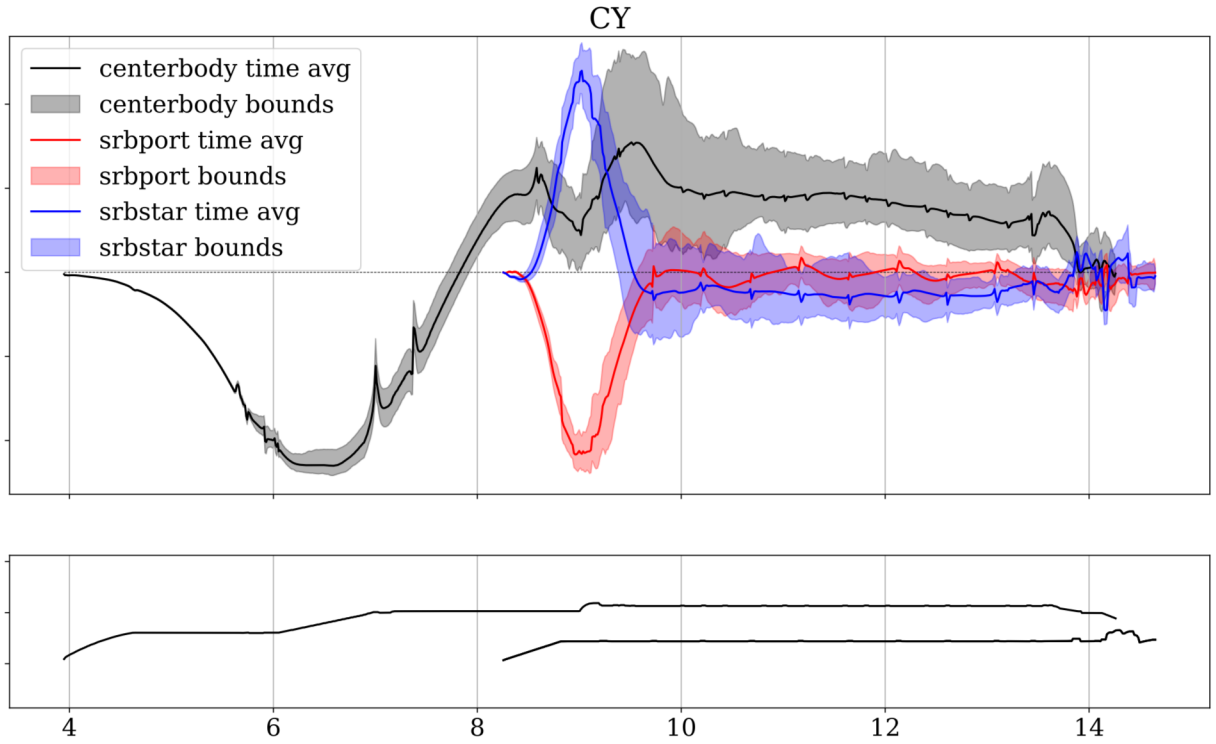
- **Not directly available from most CFD packages**
  - Computationally expensive to save surface data
  - Usually determined from a time-averaged or steady-state data set
  - Practical unsteady analysis made tractable by in-the-loop postprocessing
- **New workflow in development to record unsteady data**
- **Transient databases inform challenges like wind-induced oscillation**



Dashed Lines: Averaged
Solid Lines: Instantaneous

LINELOADS

- **Not directly available from most CFD packages**
  - Computationally expensive to save surface data
  - Usually determined from a time-averaged or steady-state data set
  - Practical unsteady analysis made tractable by in-the-loop postprocessing
- **New workflow in development to record unsteady data**
- **Transient databases inform challenges like wind-induced oscillation**
- **Unsteady lineloads can present statistics for time-averaged values**

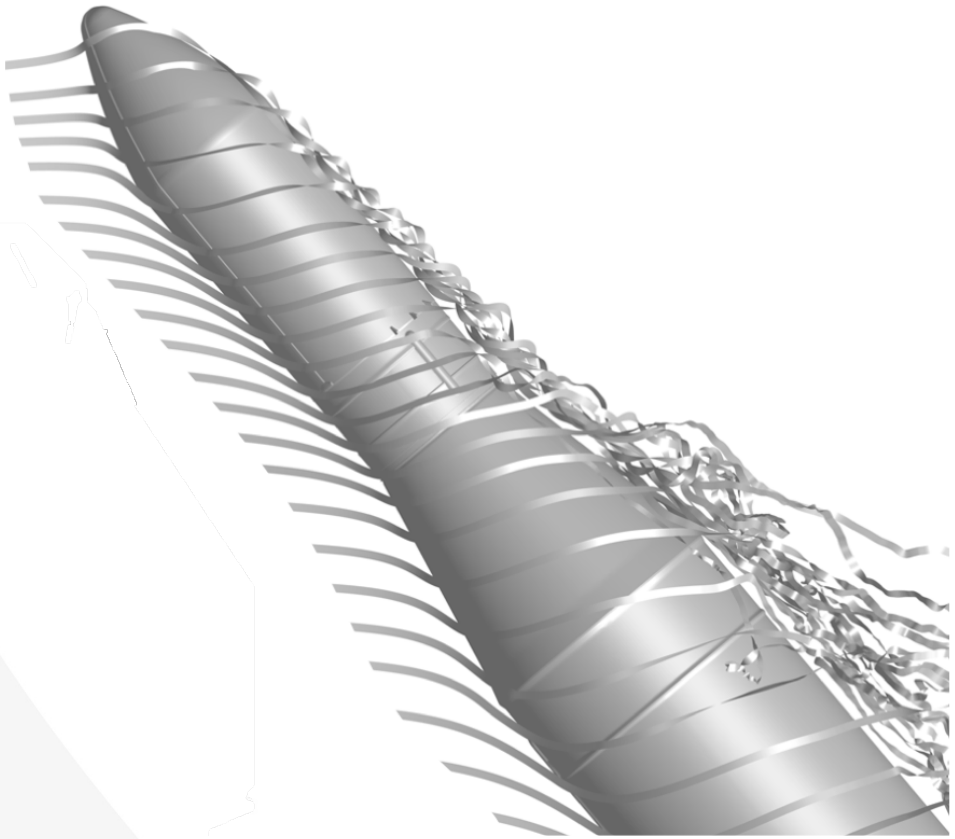


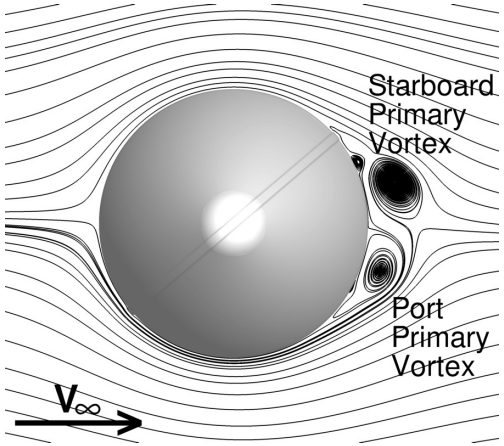
ASYMMETRIC VORTICES

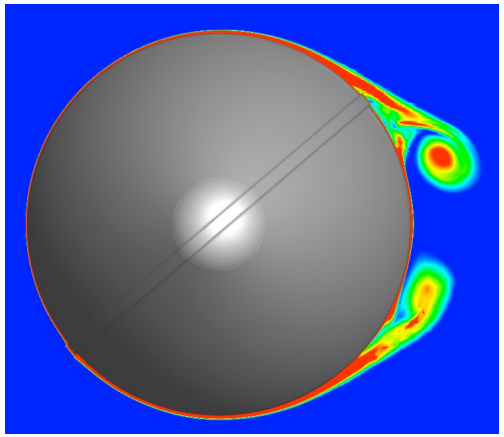
- Separation above α_P 20 deg. yields massive separation on leeward surface

ASYMMETRIC VORTICES

- Separation above α_P 20 deg. yields massive separation on leeward surface
- Asymmetric vortices occur over forebody at AOA between ~20 to ~70 deg.

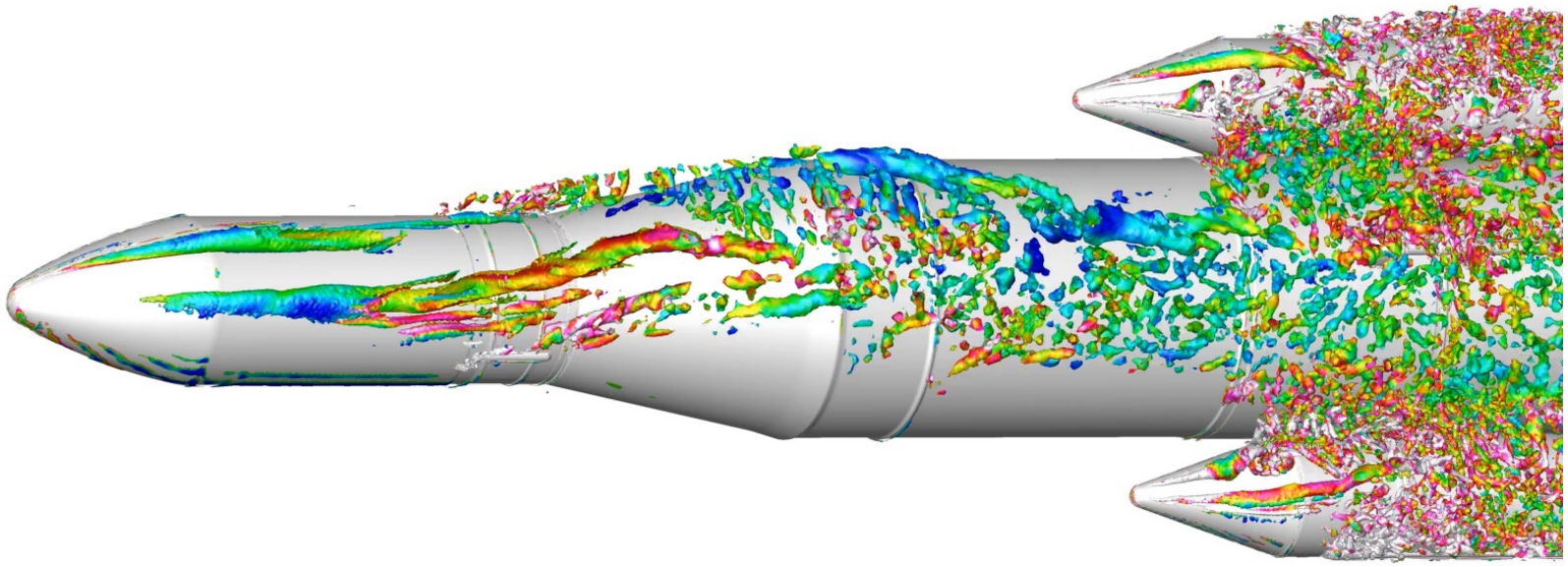






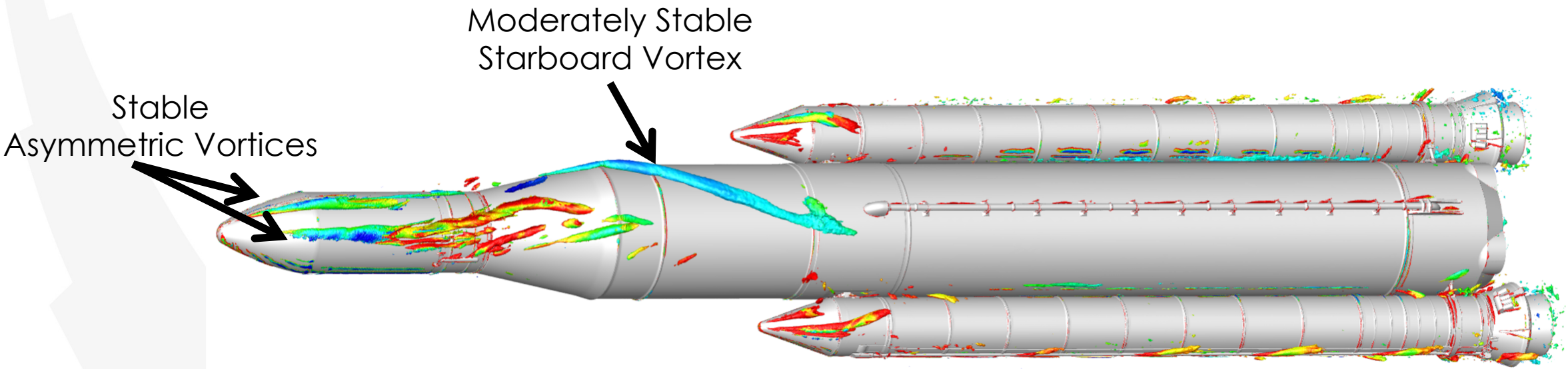
ASYMMETRIC VORTICES

- **Separation above α_P 20 deg. yields massive separation on leeward surface**
- **Asymmetric vortices occur over forebody at AOA between ~20 to ~70 deg.**
- **Isosurface of Q-criterion (Q) flooded by ω (vorticity)**
  - Massive broadband separation behind SRBs
  - Multiple stable vortices observed



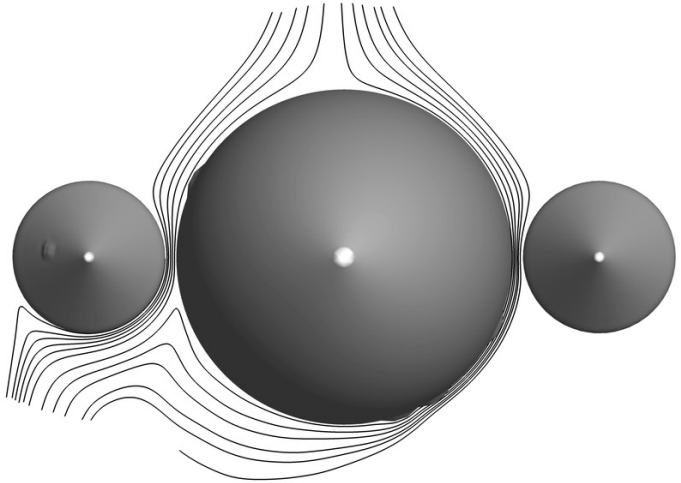
ASYMMETRIC VORTICES

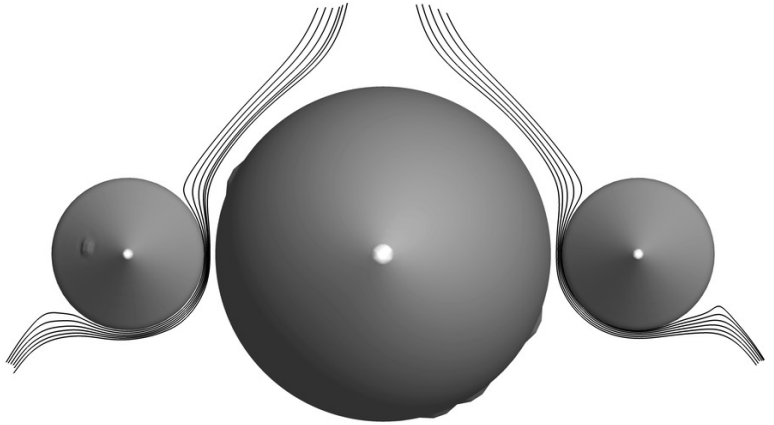
- **Separation above α_P 20 deg. yields massive separation on leeward surface**
- **Asymmetric vortices occur over forebody at AOA between ~20 to ~70 deg.**
- **Isosurface of Q-criterion (Q) flooded by ω (vorticity)**
  - Massive broadband separation behind SRBs
  - Multiple stable vortices observed

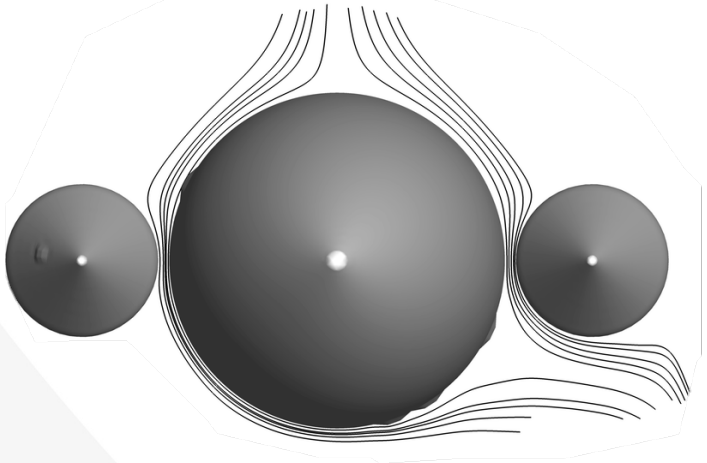


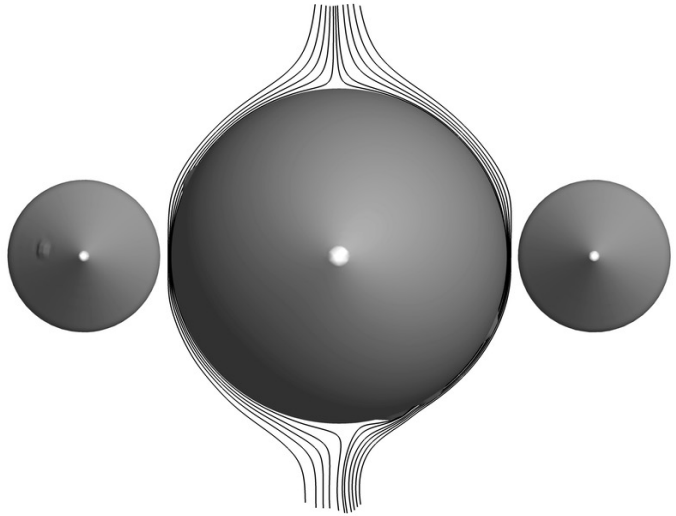
COANDA EFFECT

- **High-alpha feature (tendency of flow to remain attached to concave surface)**





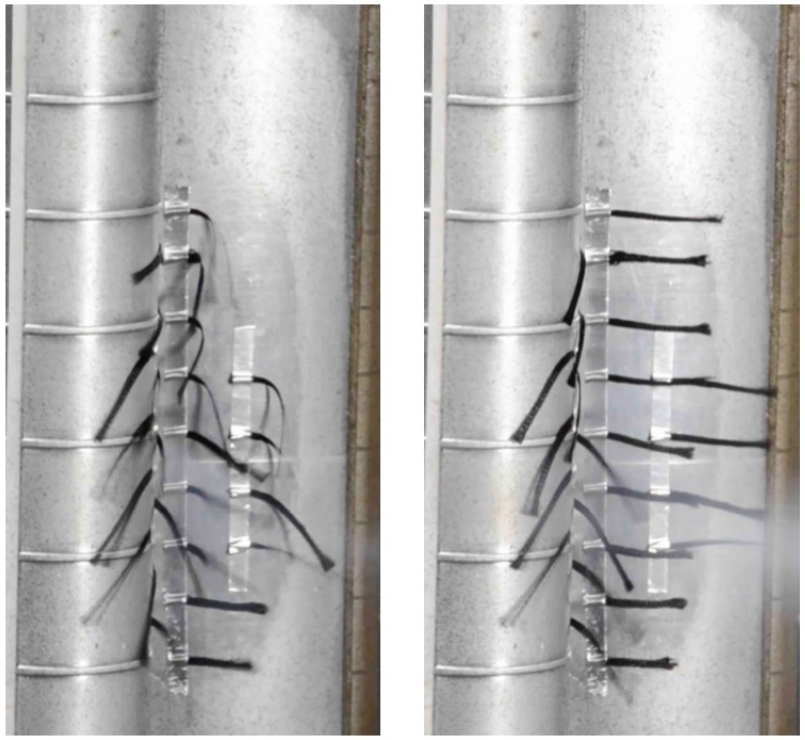




COANDA EFFECT

- **High-alpha feature (tendency of flow to remain attached to concave surface)**
- **Bistable state captured computationally a few years ago**
- **Experimental identification in 14x22 test in 2021 – flips between centerbody and Solid Rocket Boosters (SRBs)**

Snapshots



Real-Time Movie



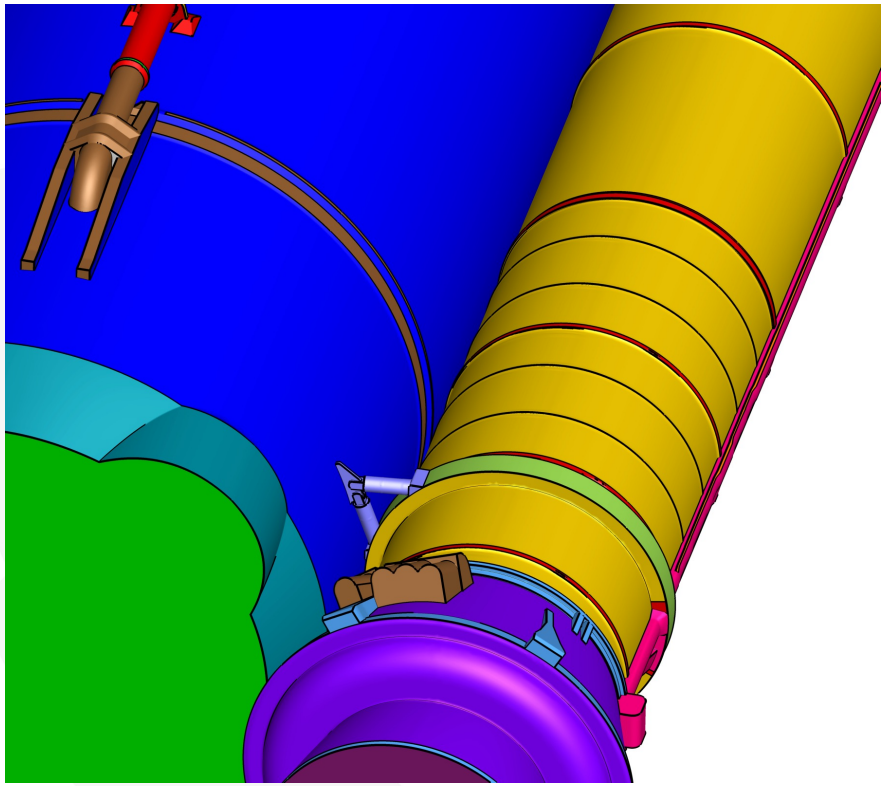
OUTLINE

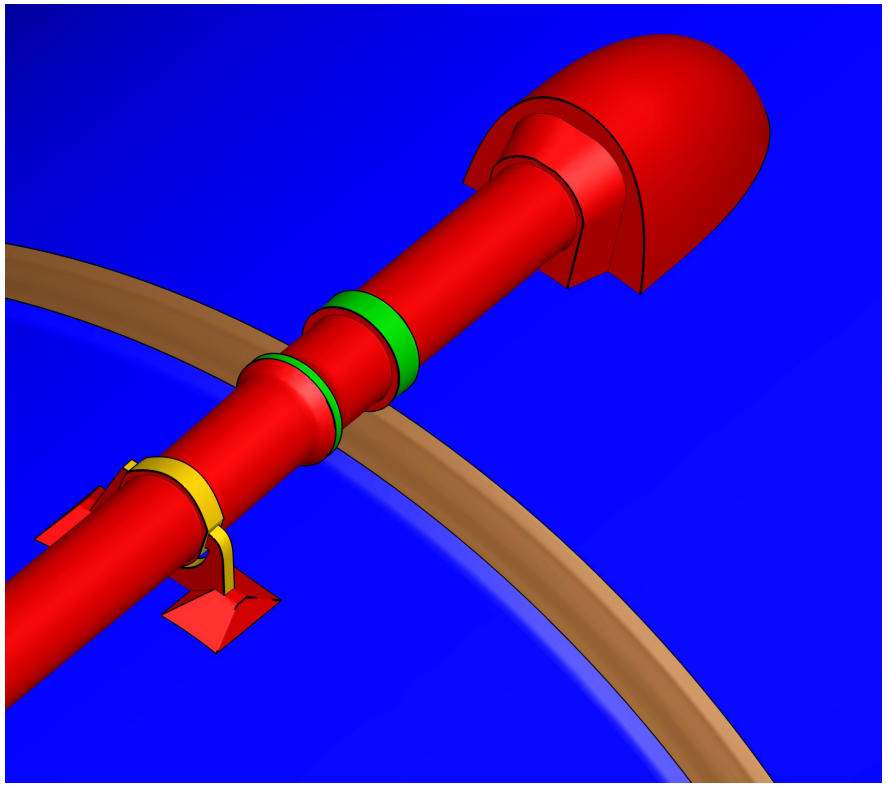
- **Introduction and Overview**
- **Methods**
  - Surface Representation
  - Grids
  - Computational Solvers
  - Computational Approach
- **Liftoff and Transition Above Tower**
- **Liftoff and Transition in Proximity of Tower**
- **Other Program Requests**



SURFACE REPRESENTATION

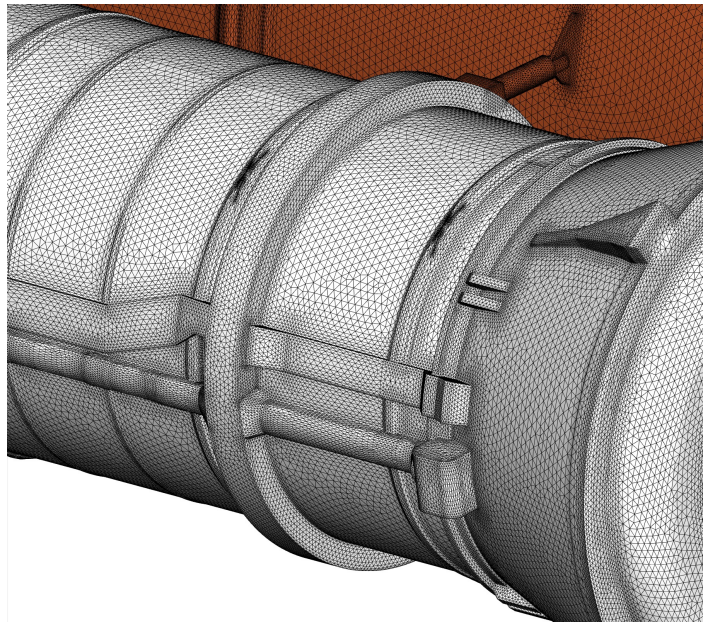
- Extremely high-fidelity CAD model
- Nearly 7,300 surfaces and 4,500 patches
- Significant support from GEOLAB group

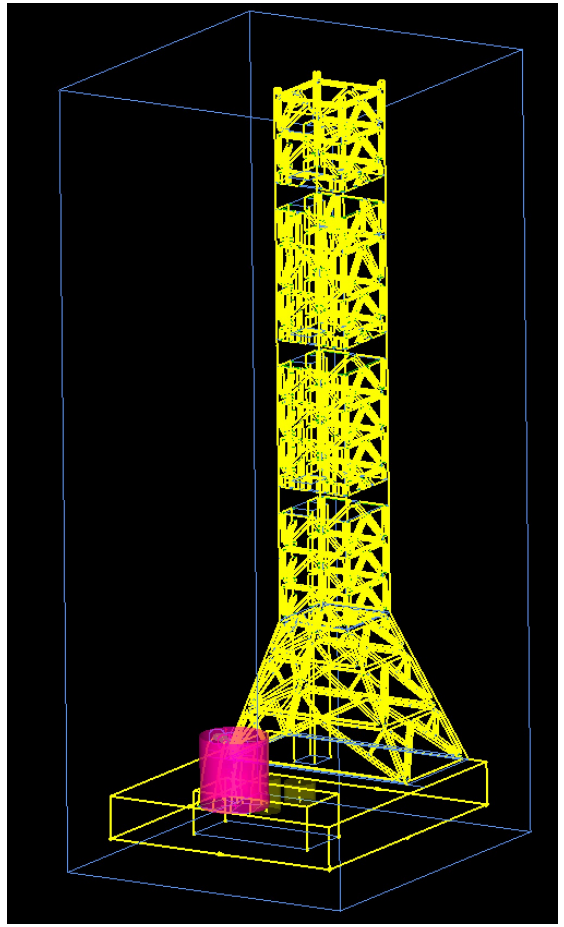




TETRUSS

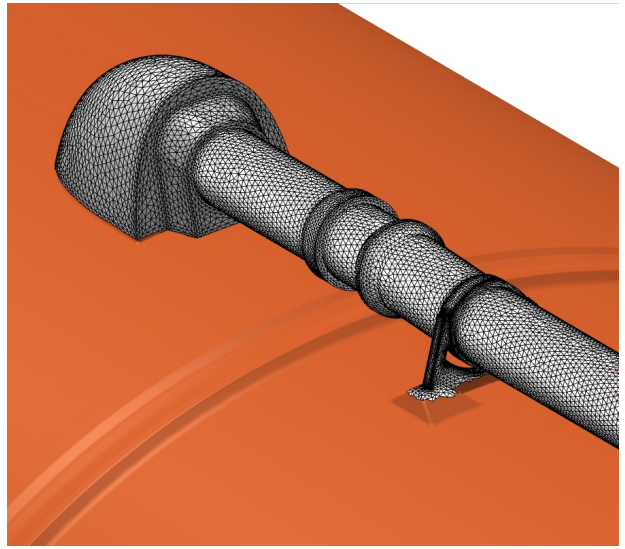
- Original grids developed with Tetrahedral Unstructured Software System (TetrUSS) package
- Hundreds of hand-placed sources on vehicle and tower
- Unstructured tetrahedron grid

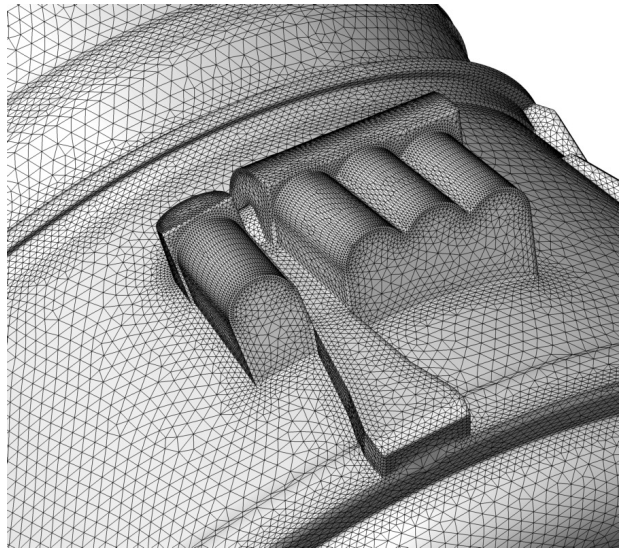




HELDENMESH

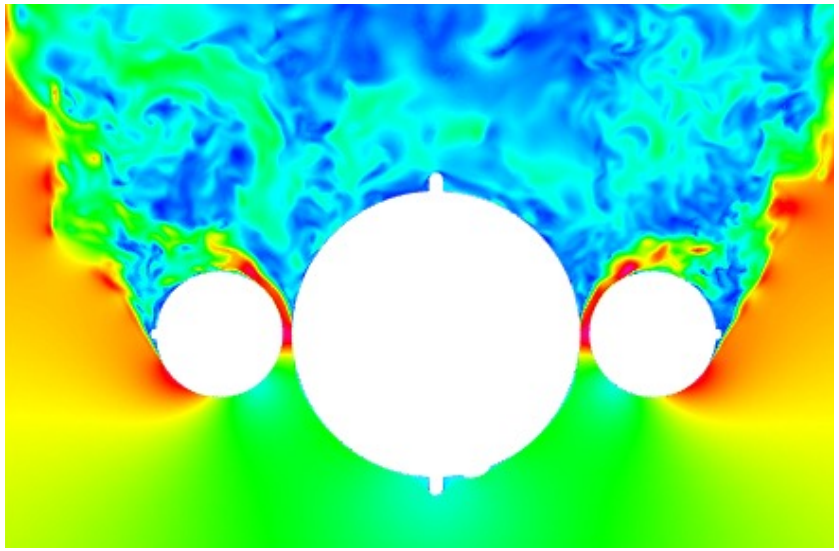
- **HeldenMesh grid generator**
  - Unstructured, mixed-element surface and volume grid generator
  - Sourcing is based on patch names (limited hand work)
- **Standard practices updated to HeldenMesh**
  - Significant saving in engineers' time for grid setup
  - Reduced cost to generate grid
  - Grids with hundreds of millions of cells can be made in minutes
- **Fine mesh needed for sufficient modeling**
  - At least four surface cells on any surface
  - Large number of surface protuberances
  - About 120 million mixed element cells in nearbody volume grid over the vehicle
  - About 100 million mixed element cells in nearbody volume grid over the tower



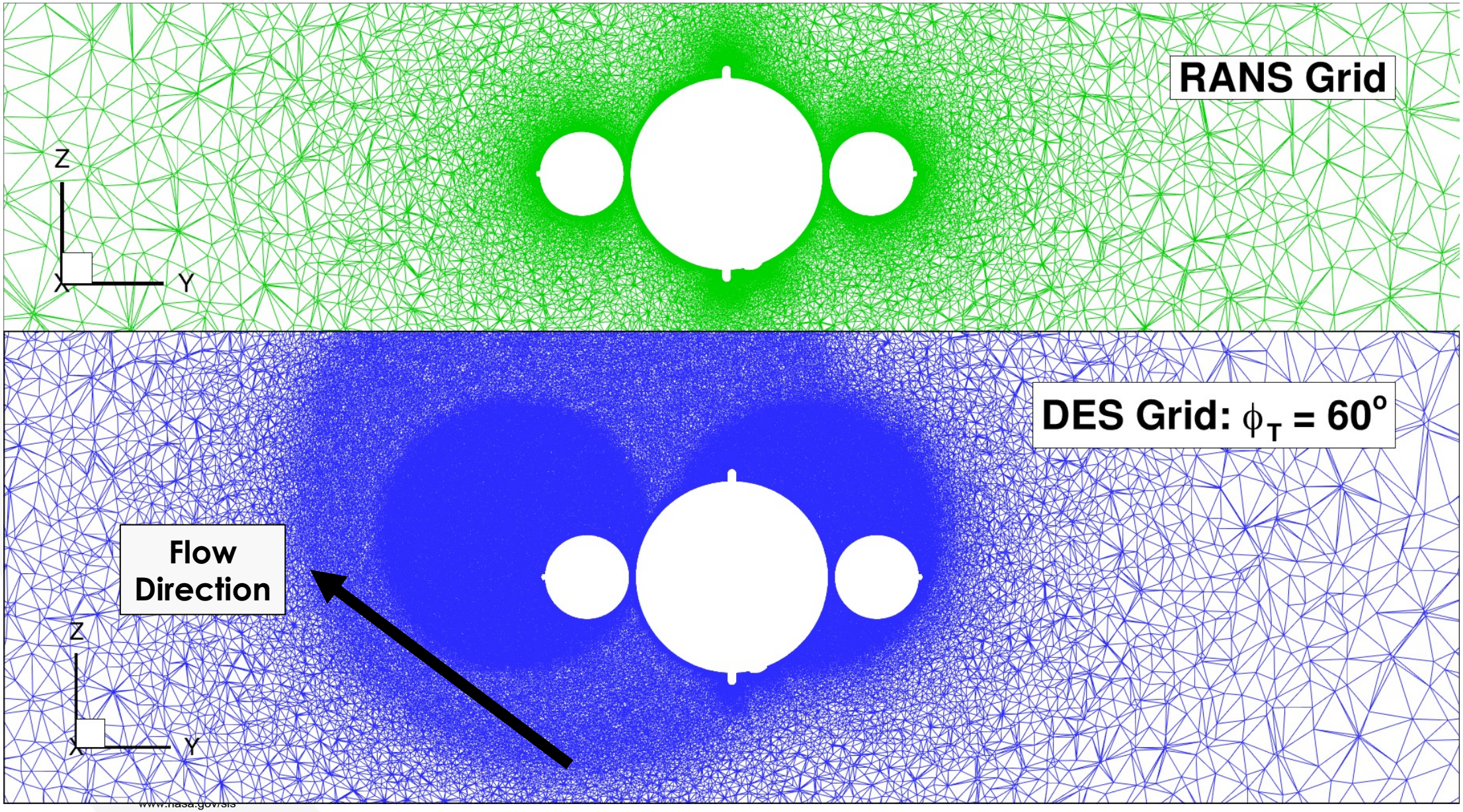


USM3D

- **Earliest Langley SLS efforts utilized NASA Langley USM3D solver**
- **Unstructured, cell centered, finite volume method**
  - Euler, Steady State RANS, URANS, and DES options
  - SA, Mentor SST, k-e turbulence models
- **Grids**
  - Only used tetrahedron for this study
  - More recent versions can use mixed element grids
  - Different grid generated for each roll angle

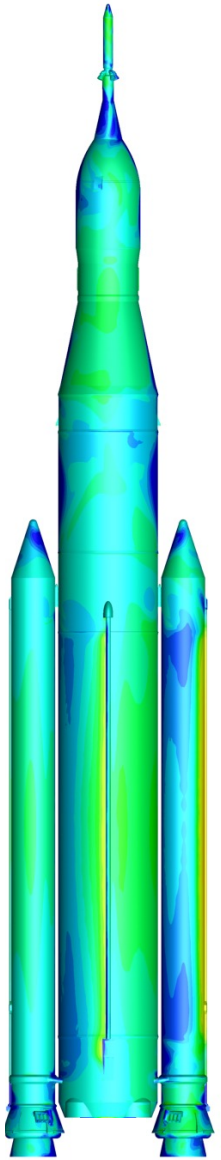


USM3D GRIDS



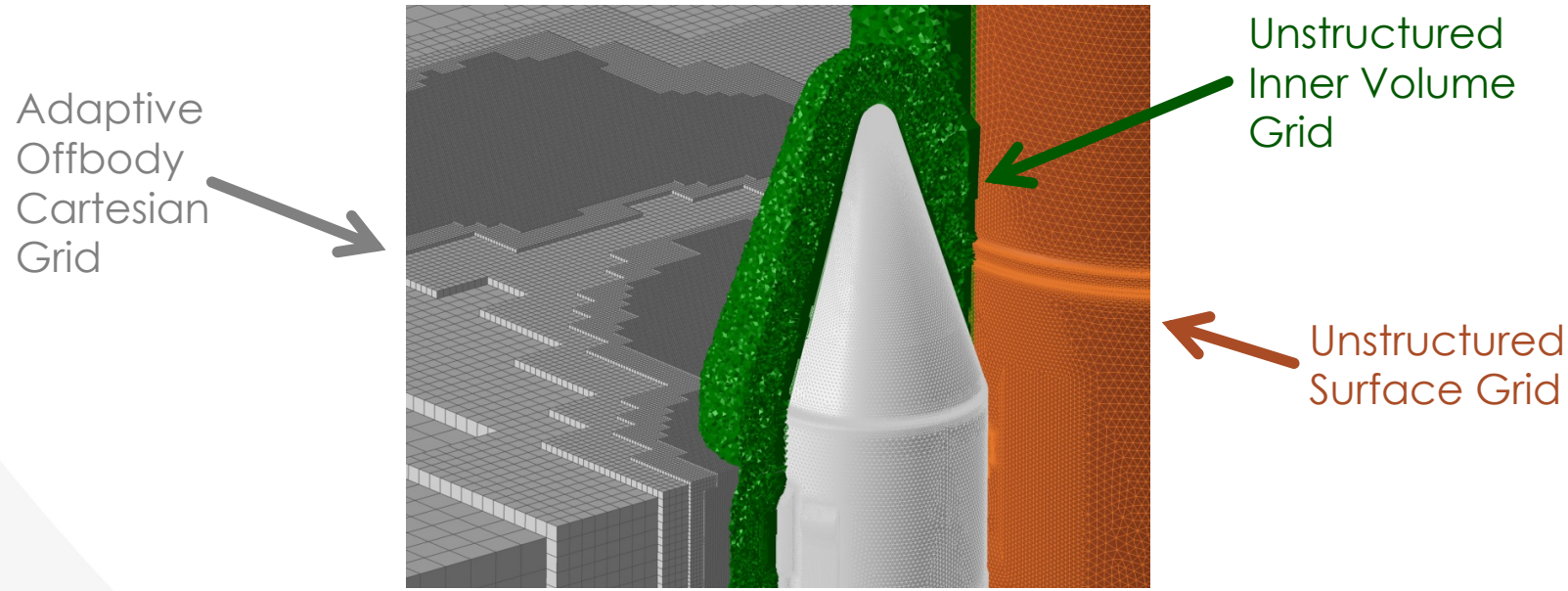
FUN3D

- **Examined for a short time to find replacement for USM3D**
- **Includes both analysis and optimization routines**
  - Also includes propulsion and thermodynamic models
  - Unstructured, node-centered, finite volume
  - Euler, RANS, URANS, and DDES schemes
  - SA, k-omega, and SST
  - Second-order upwind spatial discretization
- **Grids**
  - Homogeneous grid in the wake of the vehicle
  - Grid adaptation now available but not used in this work



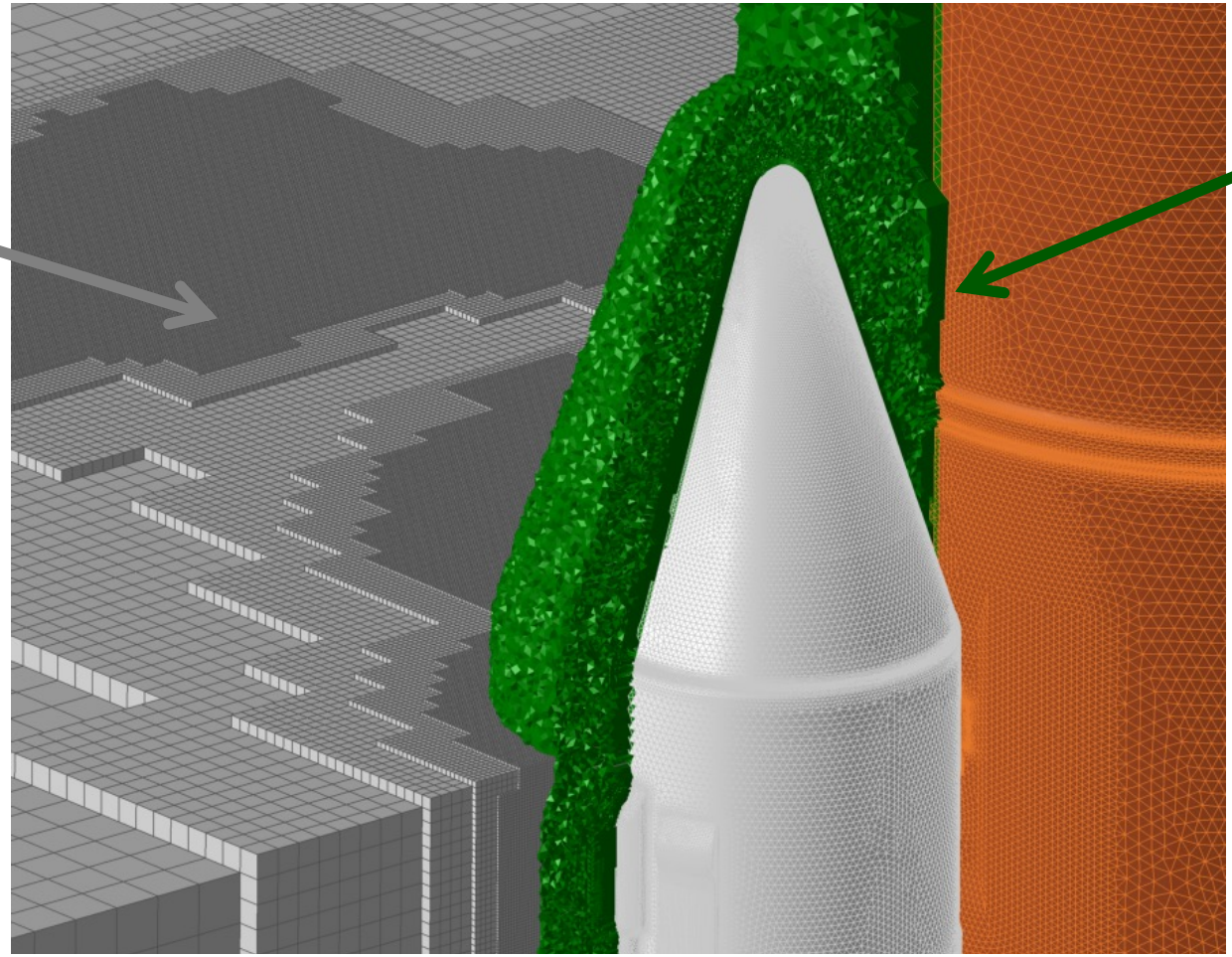
KESTREL CFD SOLVER

- **High-fidelity computational code from DoD CREATE-AV**
- **Inner/outer grid formulation**
  - Inner unstructured grid and adaptive offbody Cartesian grid
  - Unstructured grid trimmed at constant surface offset distance
  - Cartesian solver SAMAir is extremely fast and efficient
  - Greatest efficiency obtained by representing large portion of flowfield with Cartesian grid



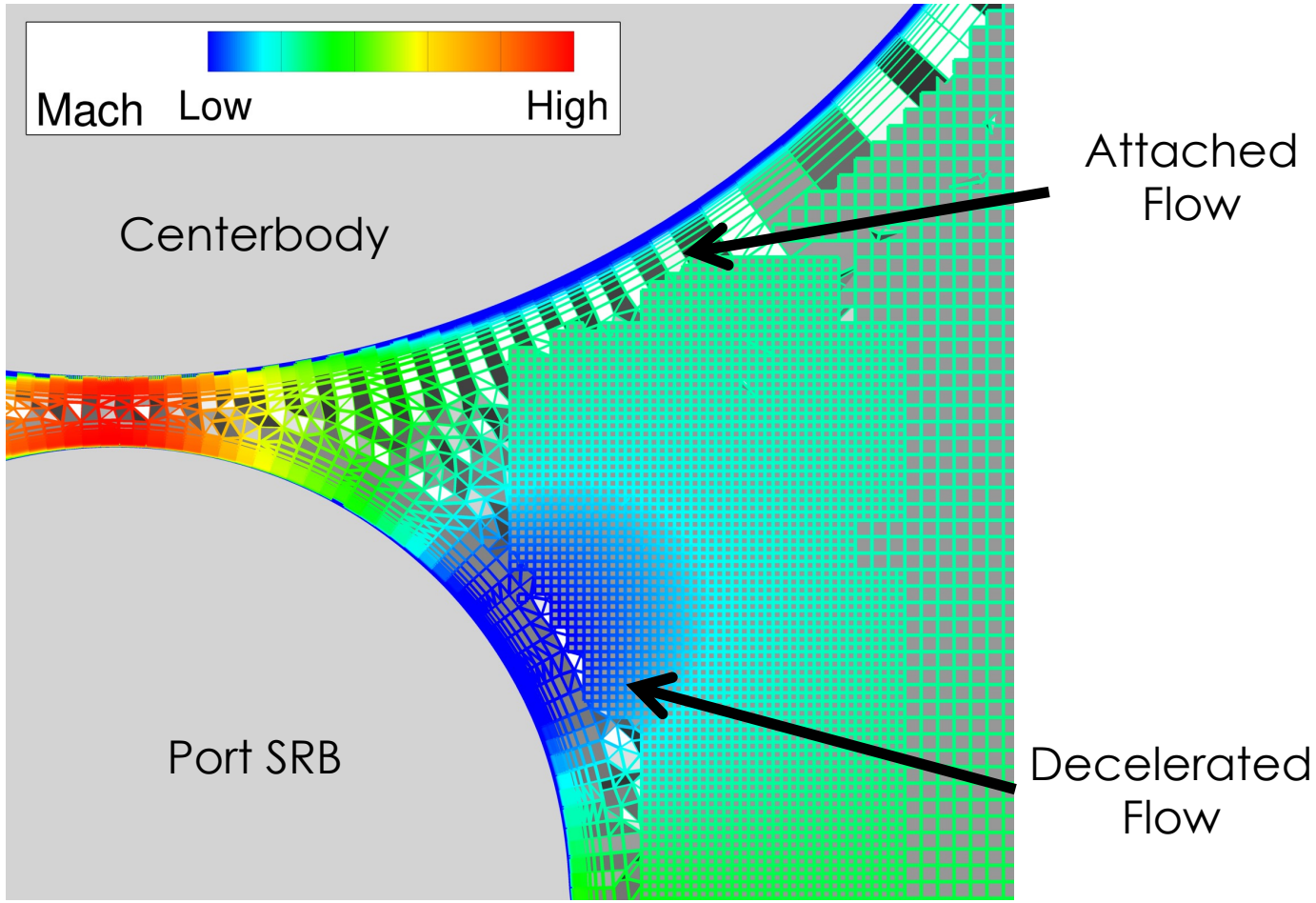
KESTREL CFD SOLVER

- **Adaptive offbody grid eliminates need for an unstructured grid at each roll angle**



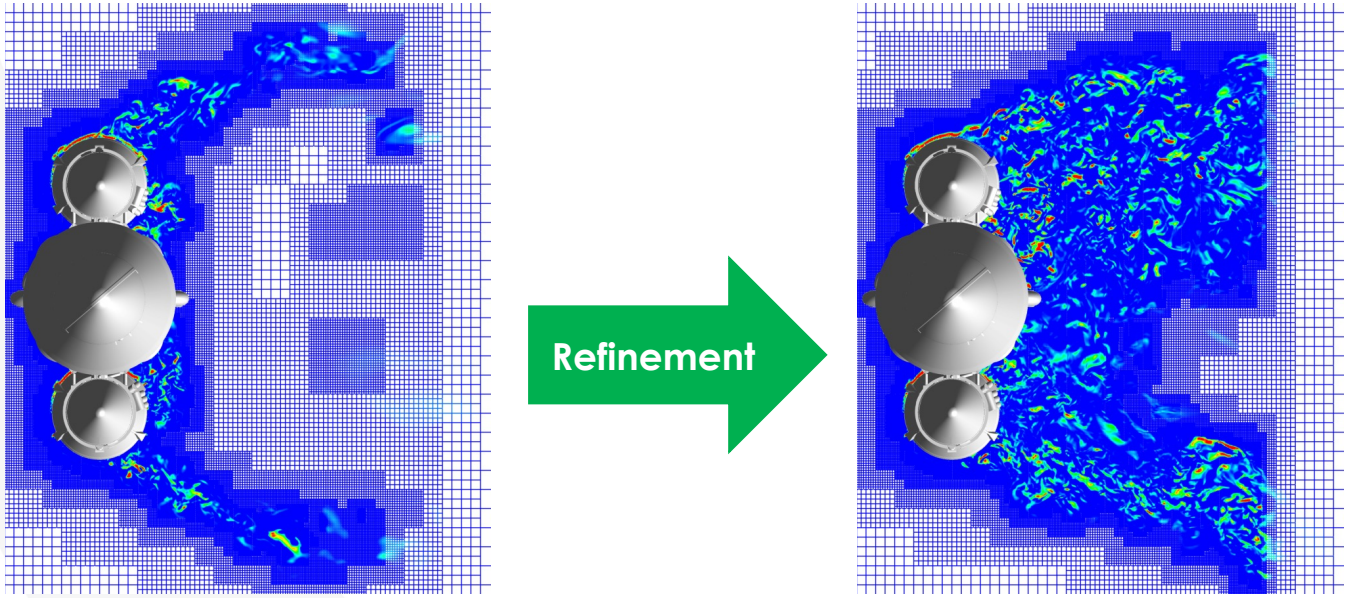
NEARBODY/OFFBODY GRID OVERLAP

- Trimmed unstructured grid (tetrahedron and prisms) are visible
- Overlapping Cartesian grid refined to capture wake aerodynamics
- Increased grid refinement in regions of high gradients



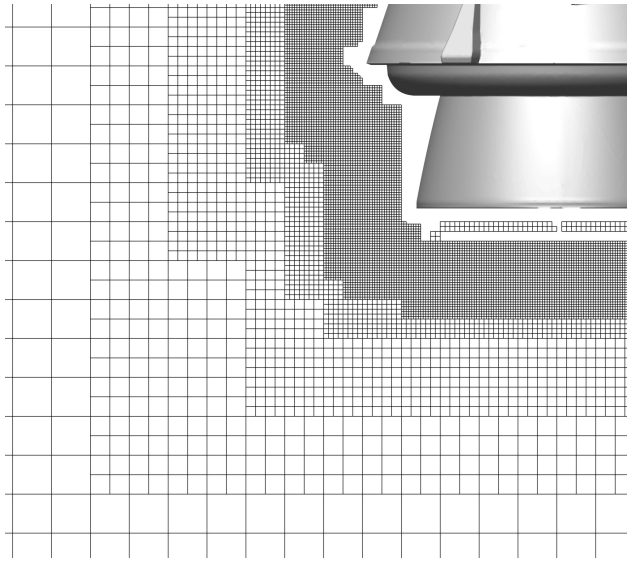
NEARBODY/OFFBODY GRID ADAPTATION

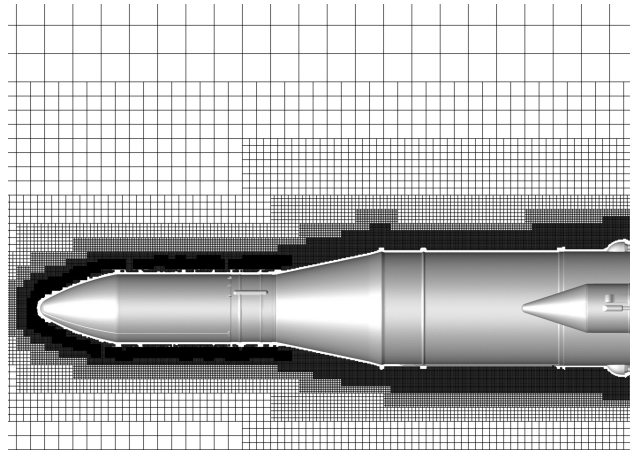
- **Solution adaptive refinement in regions of interest**
  - Mesh adaptation on outer Cartesian grid
  - Off-body grid refinement activated by exceeding a threshold of vorticity magnitude
- **Inner unstructured grid held constant**
- **Cartesian grids can be in excess of 3 billion points**



Solution setting up

Start of time averaging



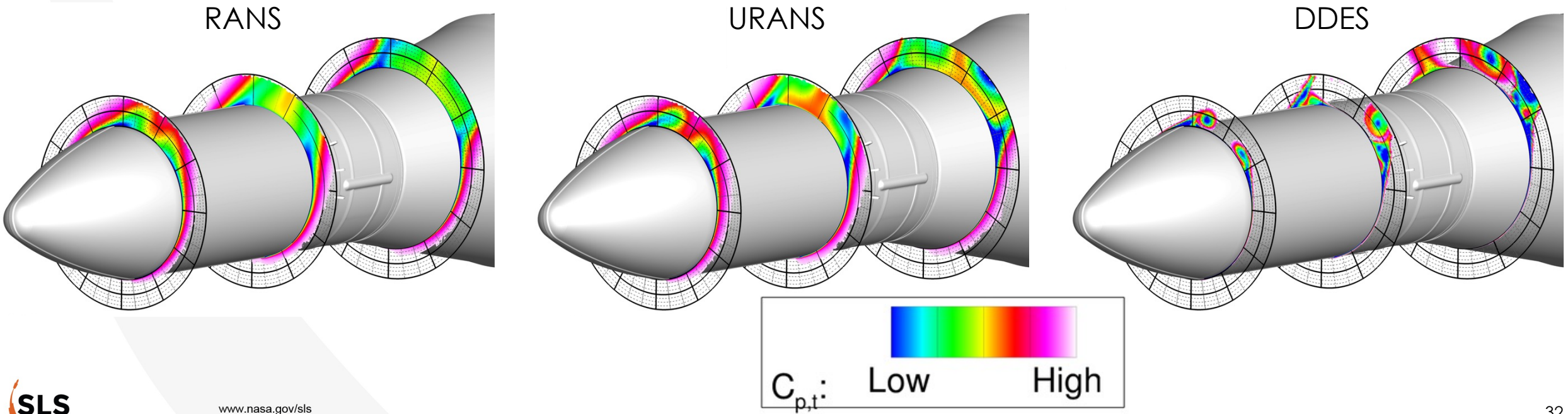


KESTREL – SELECTED CFD SOLVER

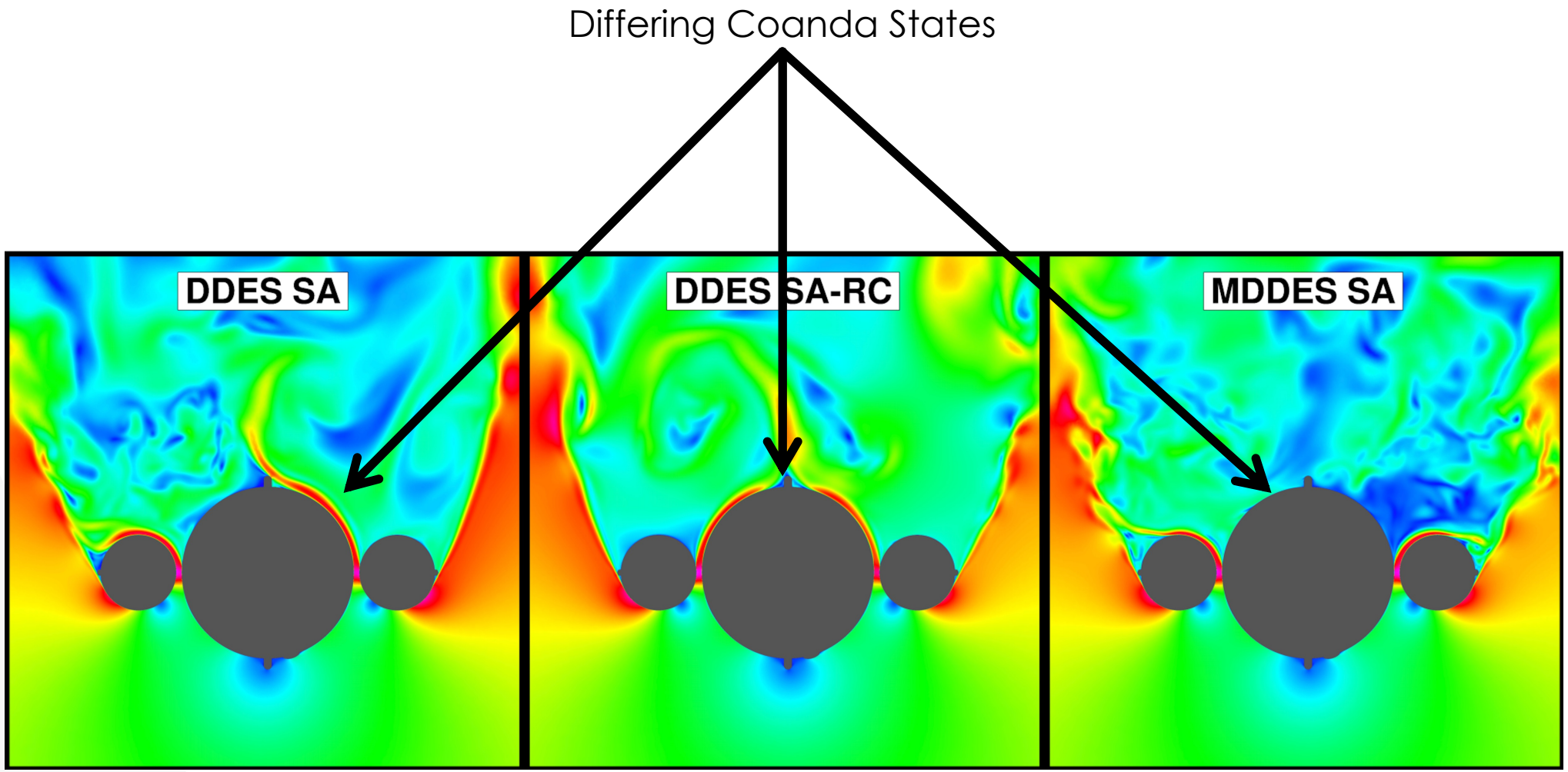
- **Kestrel contains advanced IDDES model**
  - FUN3D: MDDES
  - USM3D: DES
- **Best comparison to experimental data of codes tested**
- **Adaptive wake refinement does not require grids for each roll angle**
- **Decreased computational cost**
  - Significantly cheaper for database-level analysis (~60 simulations)
  - Faster than USM3D which was faster than FUN3D

COMPUTATIONAL APPROACH – TEMPORAL SCHEME

- **Massively-separated flow present on leeward side of vehicle**
- **Nondimensional total head plotted (1=full momentum; 0=no momentum)**
- **DDES models needed to accurately capture the flowfield**
- **RANS and URANS fail to capture the extent of the wake and intensity of the asymmetric vortices**



COMPUTATIONAL APPROACH – TURBULENCE MODEL

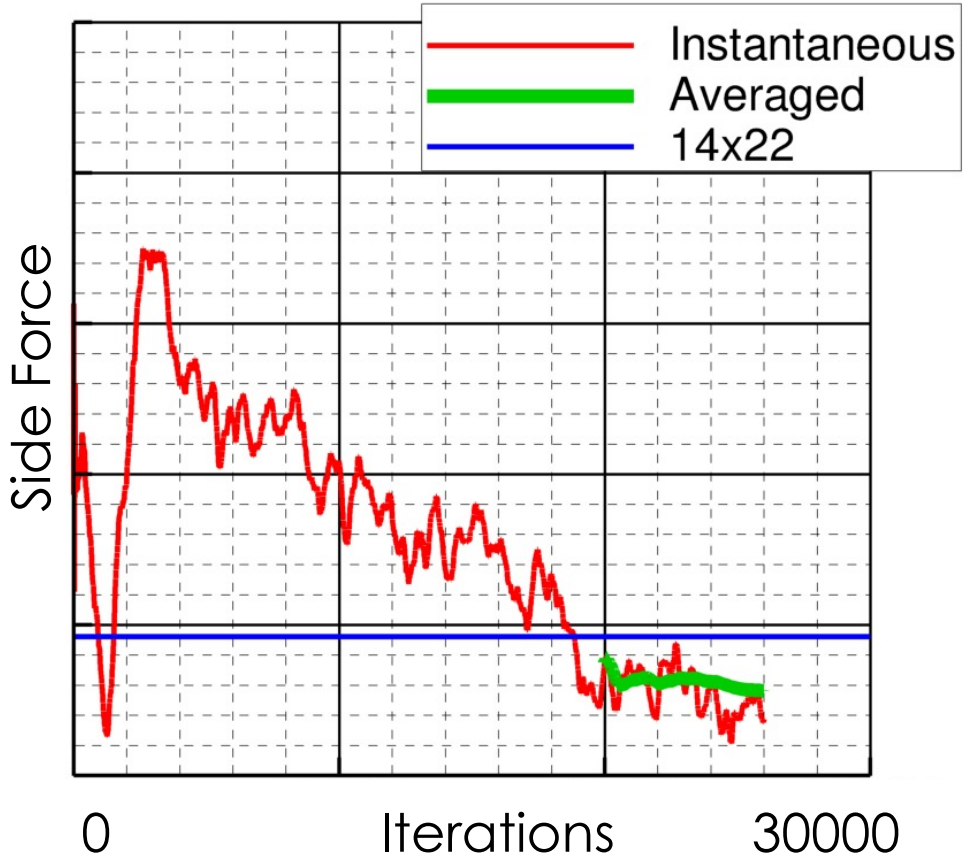


COMPUTATIONAL SETUP ESTABLISHED

- **Significant effort to quantify independent effects of 12 key settings**
- **Best practices established and quantified**
  - SA DDES
  - KCFD 2nd-order spatial discretization
  - SAMAir 3rd-order spatial discretization
  - Critical to run solution long enough to set up and reach a statistically-steady state
- **Nondimensional time step established**

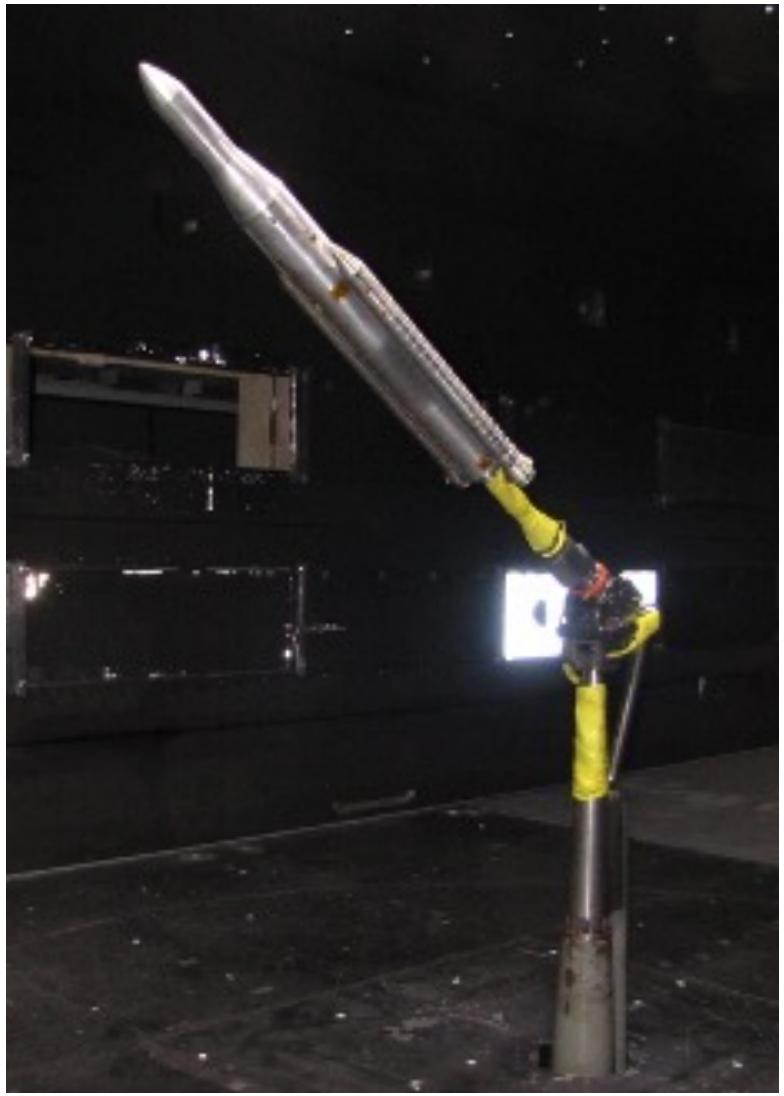
$$dt^* = \frac{dt\ V_\infty}{D_{core}} = 0.00369$$

- **Good comparison to experimental data**



OUTLINE

- **Introduction and Overview**
- **Methods**
- **Liftoff and Transition Above Tower**
  - Computational Data Sets
  - Reduced-Order Modeling
- **Liftoff and Transition in Proximity of Tower**
- **Other Program Requests**

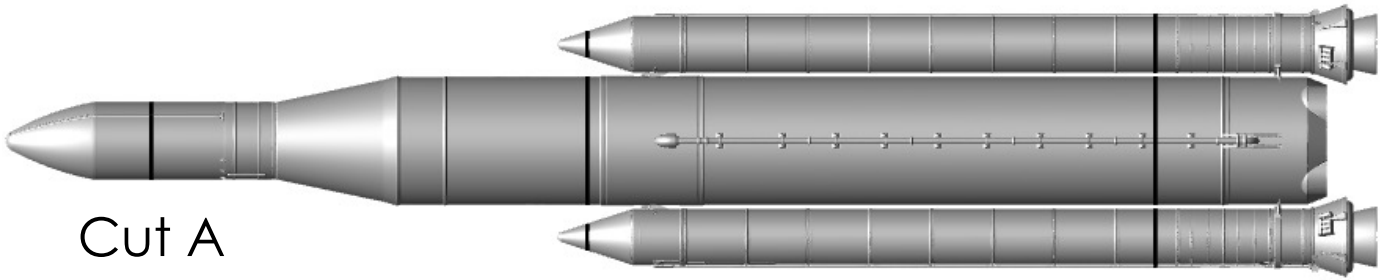


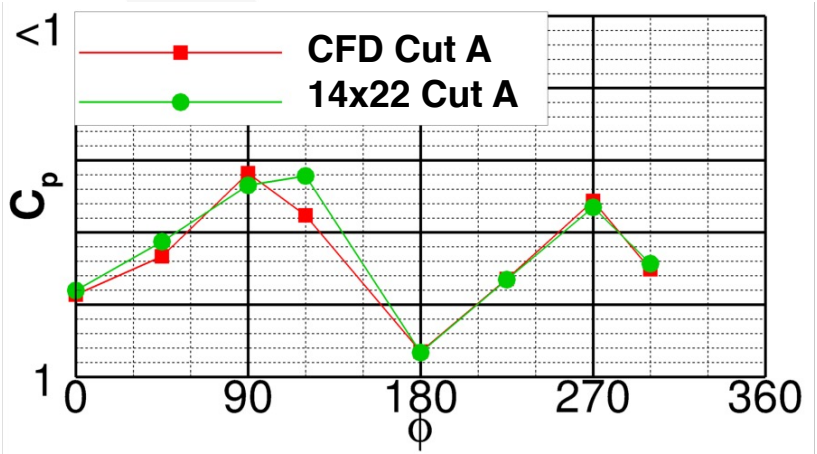
KESTREL DATABASE

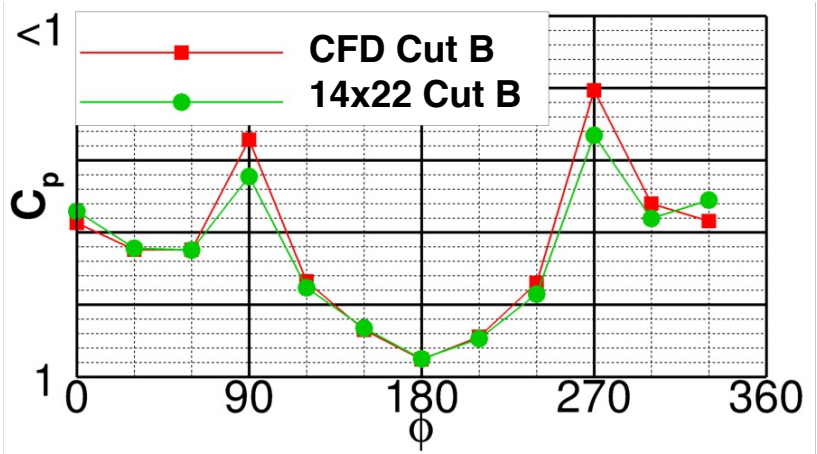
- **Vehicle subjected to a large range of freestream conditions**
- **Approximately 300 break points in the database**
  - Angle of attack from 0 to 90 deg. at 5 deg. increments
  - Roll angle from 0 to 360 deg. at 15 deg. increments
- **Typical run is three to five days on ~1,600 processors**
- **CFD results have a high level of accuracy, yet the simulations are expensive**

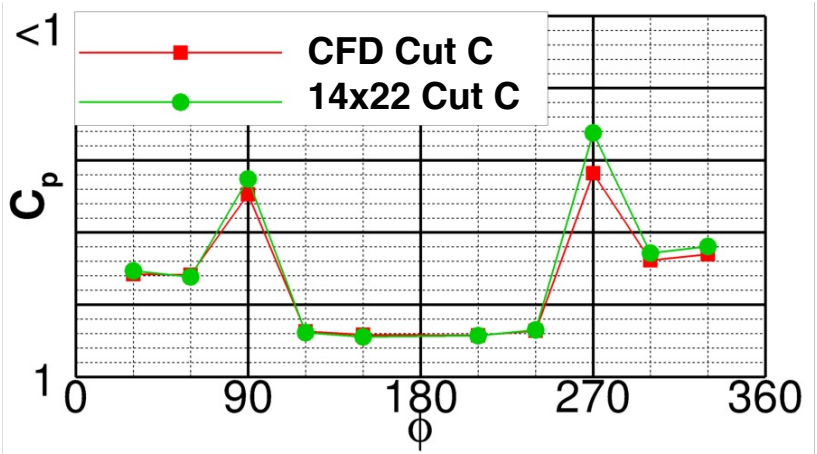
CFD TO EXPERIMENT COMPARISONS

- Data compared to 2021 test in NASA Langley 14x22 tunnel (feet)
- Excellent agreement seen at a range of body station cuts
- Conditions of α_P 50 deg. and Φ_P 0 deg.

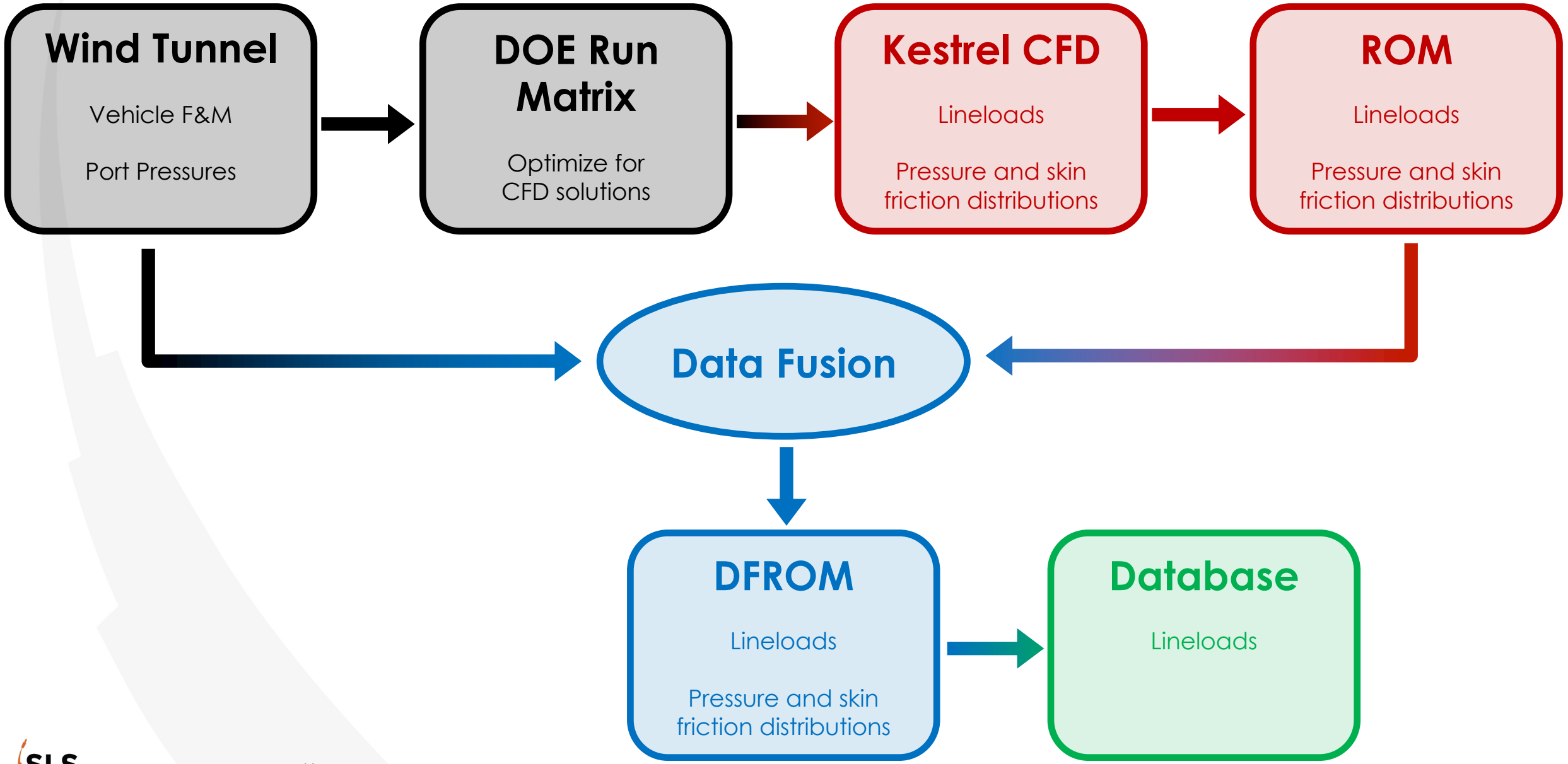








DATABASE DEVELOPMENT



REDUCED ORDER MODELING

- **Proper Orthogonal Decomposition with interpolation on the physical parameters**
- **Seek an underlying basis function which can be applied to new conditions**

$$\psi = \mathbf{S}\ \mathbf{V}$$

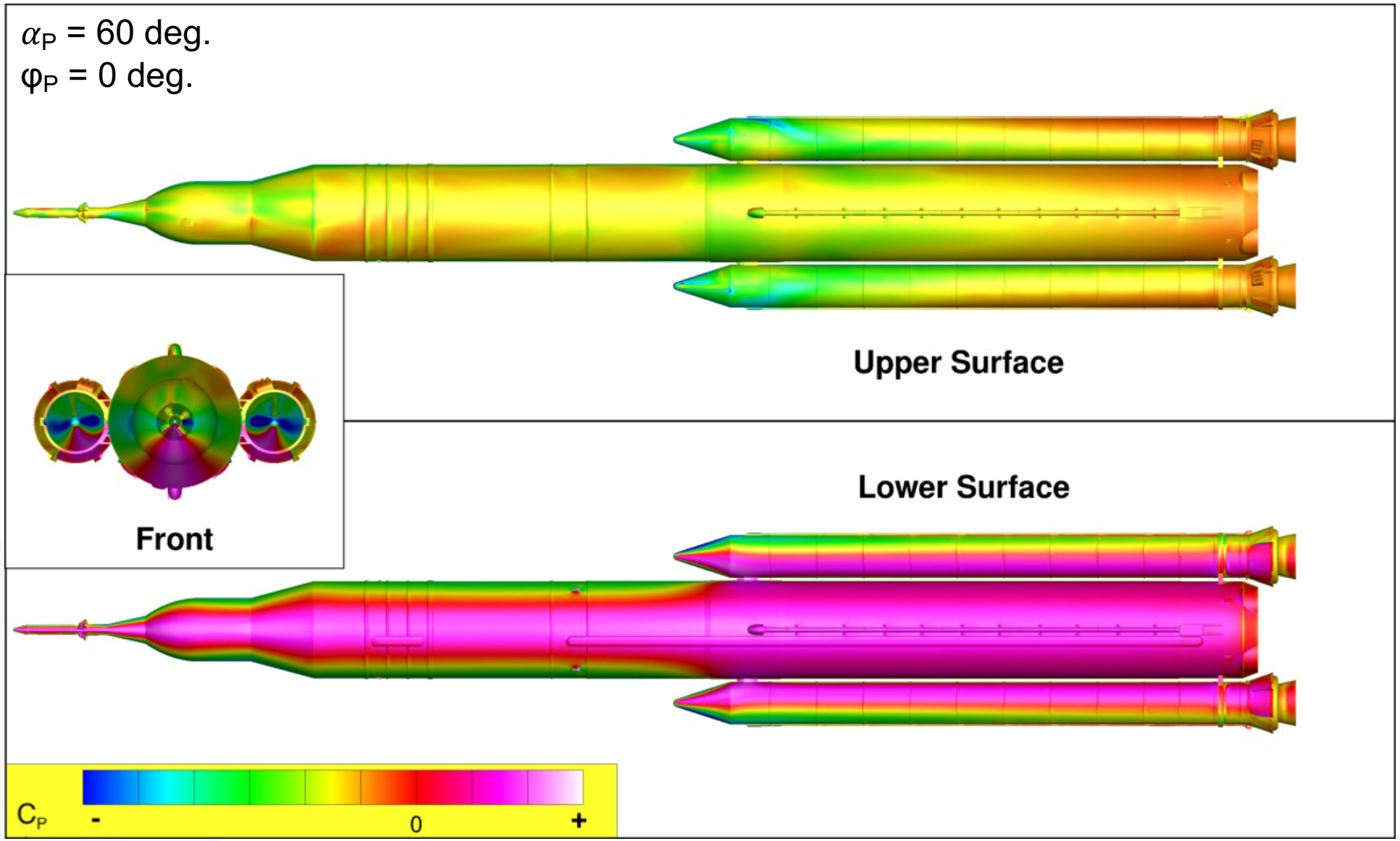
S: CFD surface data matrix
V: transformation matrix
ψ: basis function

- **Inversion of equation yields a resultant CFD matrix surface**

$$S(\alpha_P, \phi_P) = \sum_{i=1}^{n} a_i \cdot \psi_i$$

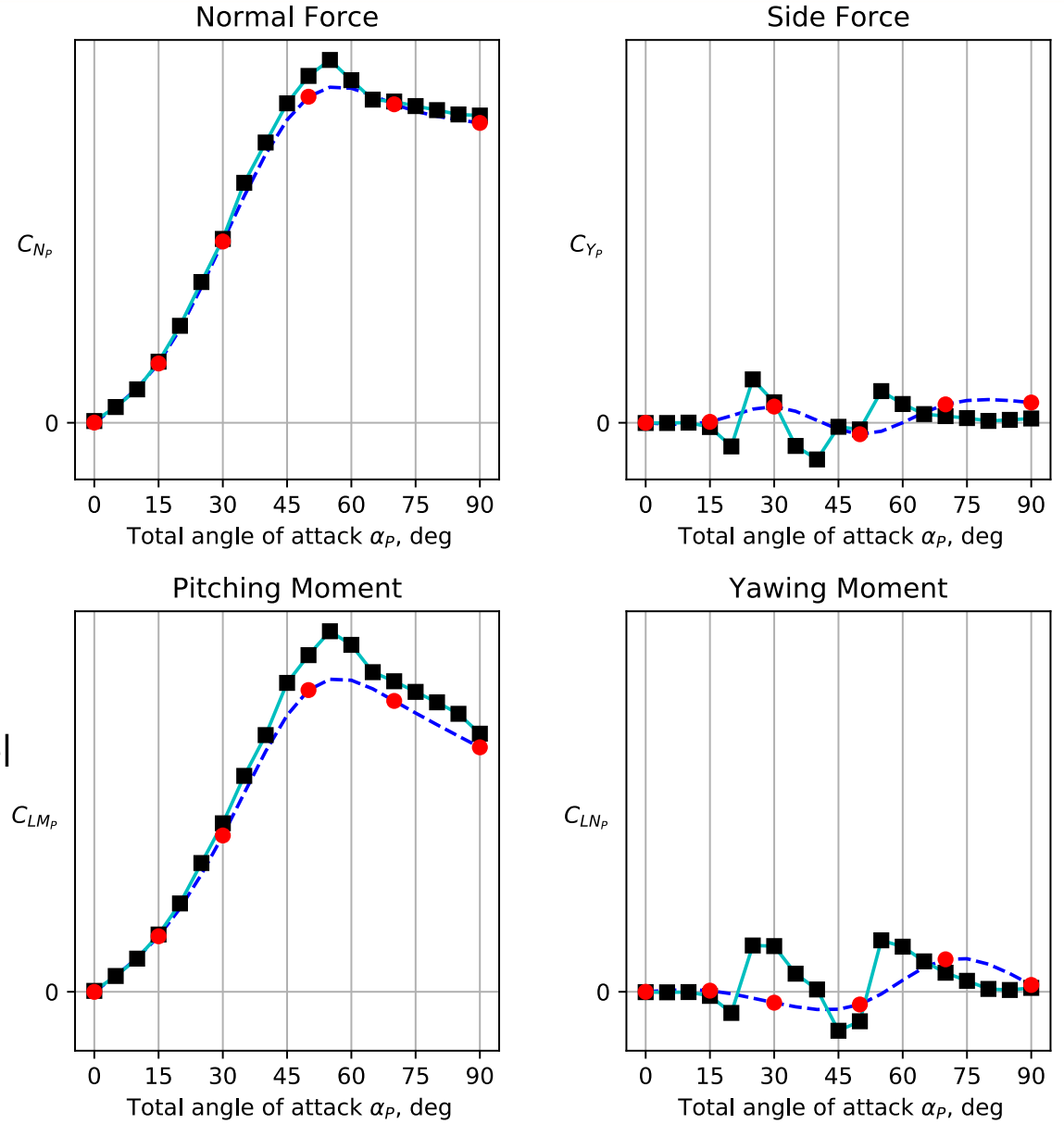
where $a_i = f(\alpha_P, \phi_P)$

ROM-GENERATED SURFACE PRESSURE



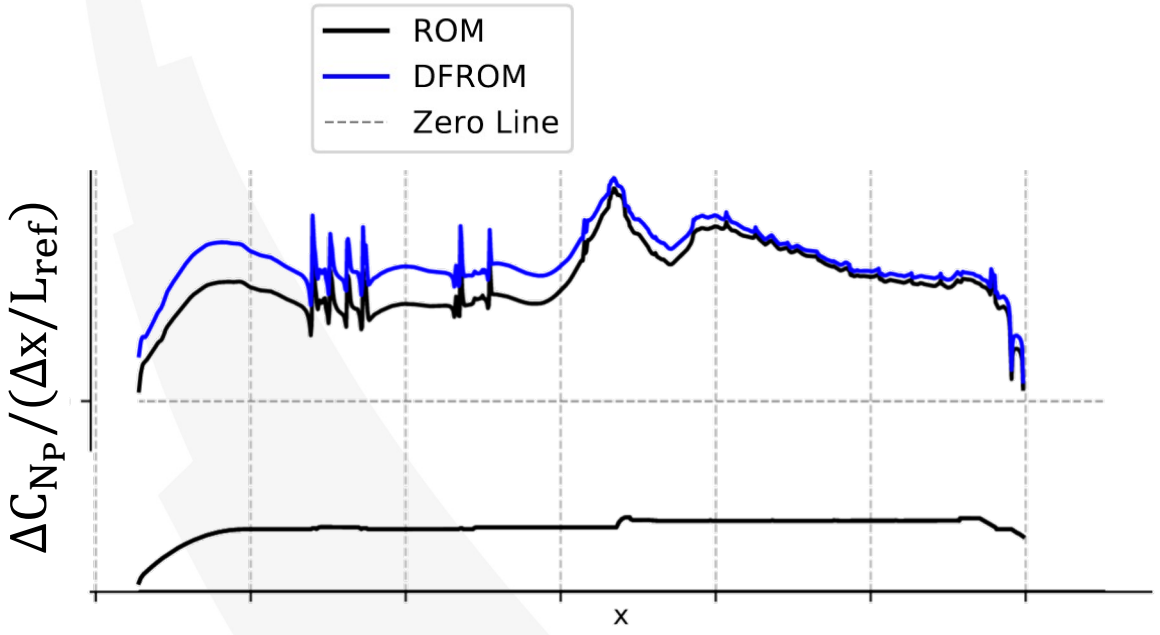
DATA-FUSED REDUCED ORDER MODELING

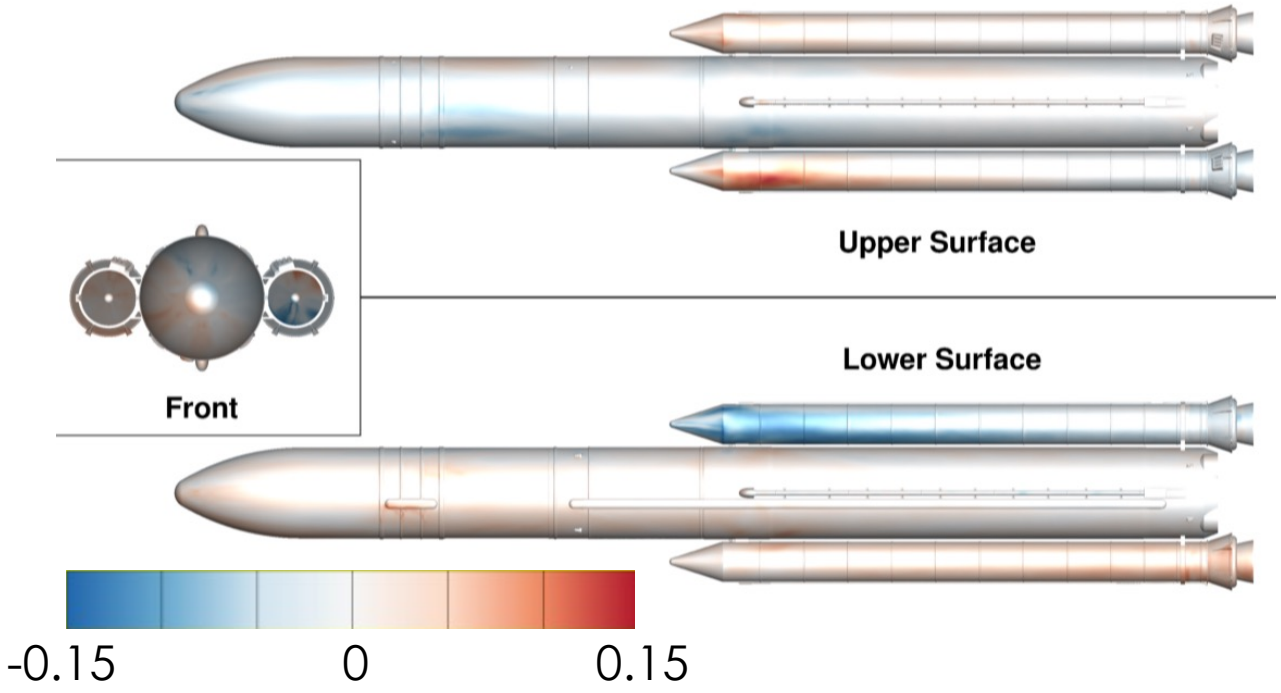
- **Data indicate CFD and ROM underpredict pitching moment and normal force**
- **Baseline ROM supplemented with known experimental data sets**



DATA-FUSED REDUCED ORDER MODELING

- **Data indicate CFD and ROM underpredict pitching moment and normal force**
- **Baseline ROM supplemented with known experimental data sets**
- **Adjustments applied with database-level analysis**





$\Delta C_P = C_{P,DFROM} - C_{P,ROM}$

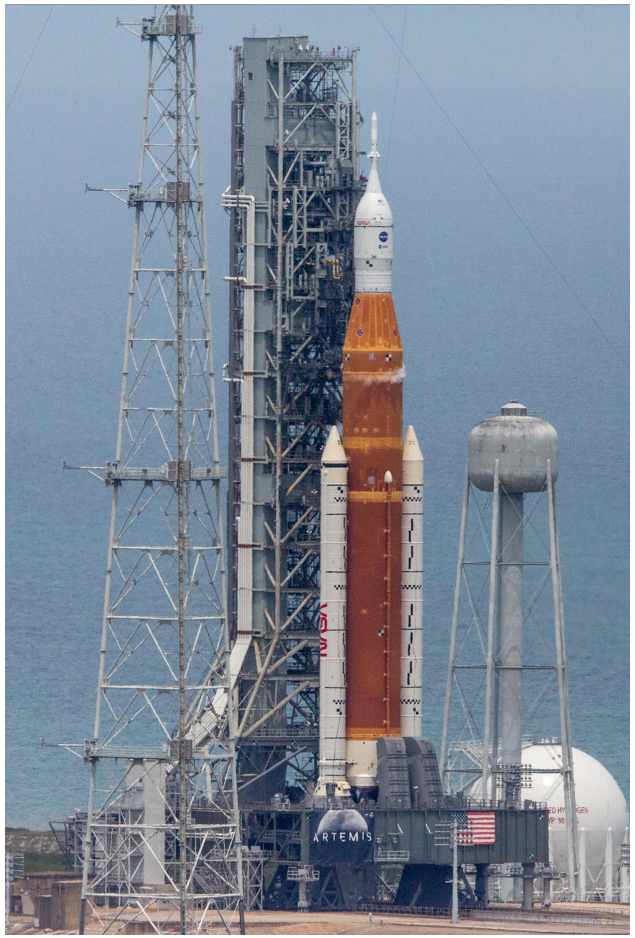
OUTLINE

- Introduction and Overview
- Methods
- Liftoff and Transition Above Tower
- Liftoff and Transition in Proximity of Tower
  - Tower Configurations
  - Database
  - Comparisons to Experimental Data
- Other Program Requests



TOWER SIMULATIONS

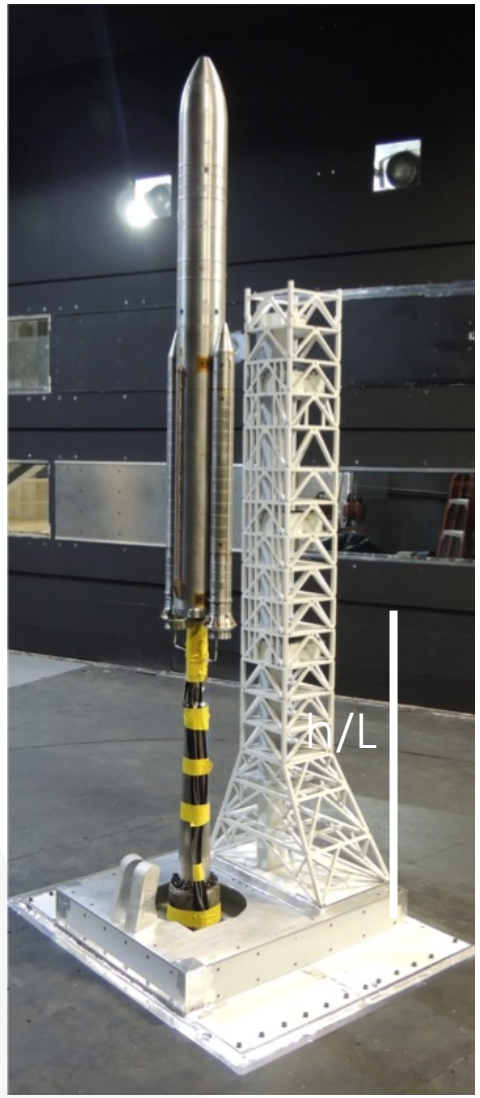
- **The effect of launch tower can be quite significant**
  - Substantial loft support obtained from the GEOLAB group
  - Includes the tower structure, elevator shaft, and Crew Access Arm
- **Challenging computational state**
  - Unsteady feedback between the vehicle and tower
  - Range of azimuth angles requires a large database
  - Simulations are extremely large and can exceed 3 billion cells



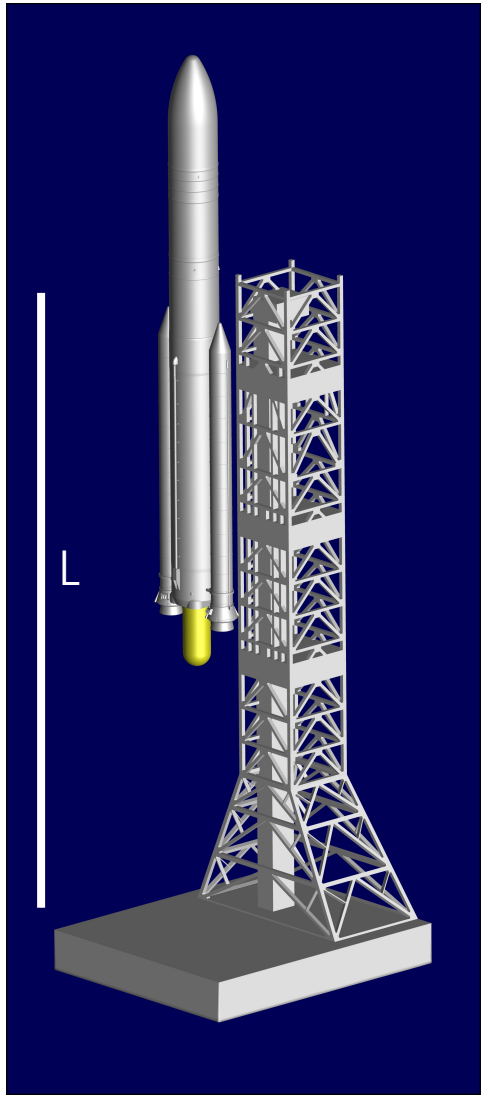


VEHICLE LIFTOFF GEOMETRY

Tunnel Block 1B
Cargo with ML-1ex



CFD Block 1B
Cargo with ML-1ex



Tunnel Block 1B
Crew with ML-2

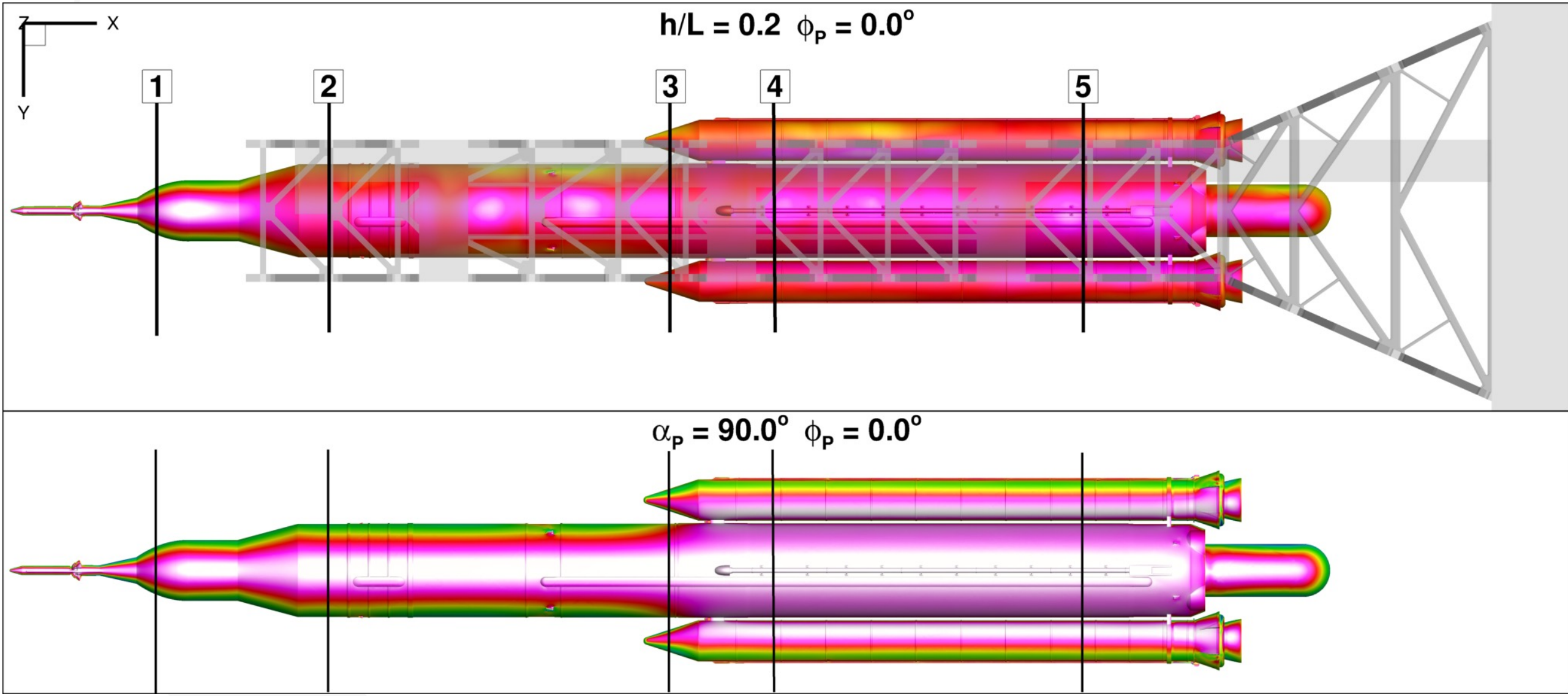


KESTREL DATABASE

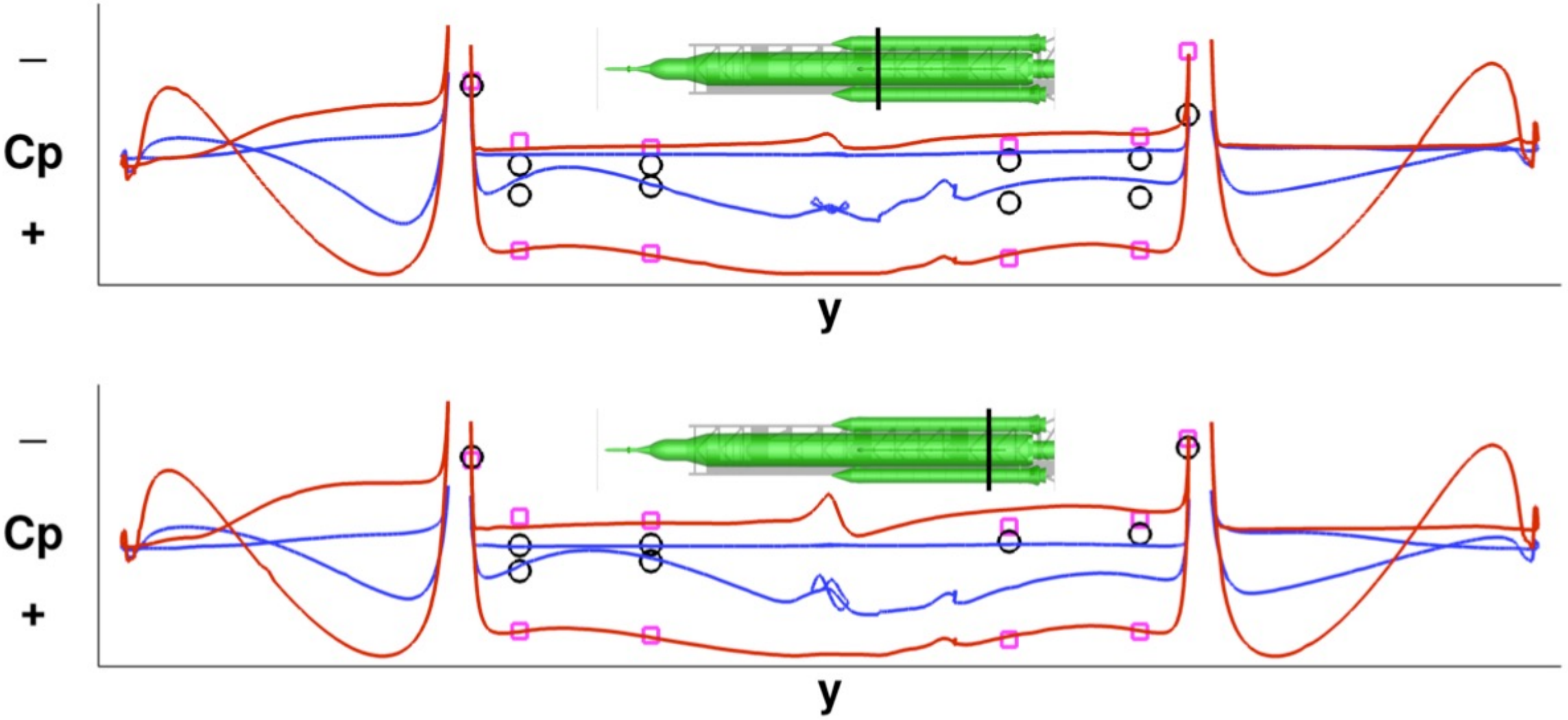
- Extraordinarily large simulations required a decreased size of the run matrix
- Limited run matrix in rocket h/L and roll angles
- Conditions selected with input from Loads and GNC groups at MSFC
- Matched to wind tunnel conditions (Mach 0.183 and 615,000 Reynolds number)

h/L	ϕ_P, deg	End-User	h/L	ϕ_P, deg	End-User	h/L	ϕ_P, deg	End-User
0.0	0	Loads	0.2	0	Devel	0.915	60	GNC
0.0	60	Loads	0.2	180	GNC	0.915	180	GNC
0.0	90	Loads	0.5	180	GNC	0.915	270	GNC
0.0	180	Loads/GNC	0.8	180	GNC	0.915	300	GNC
0.0	270	Loads						

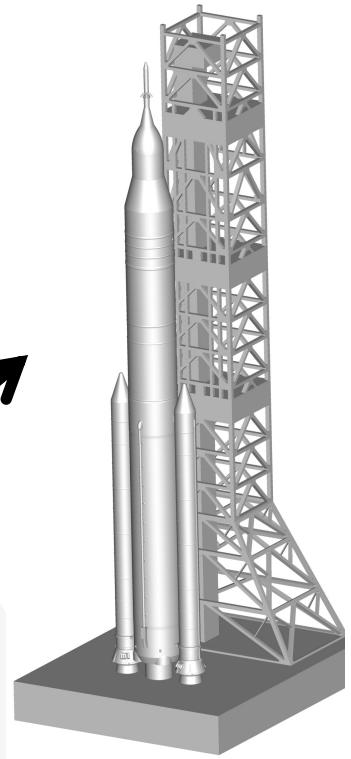
WINDWARD SURFACE C_P AT H/L=0.2 Φ=0° WITH AND WITHOUT ML1EX



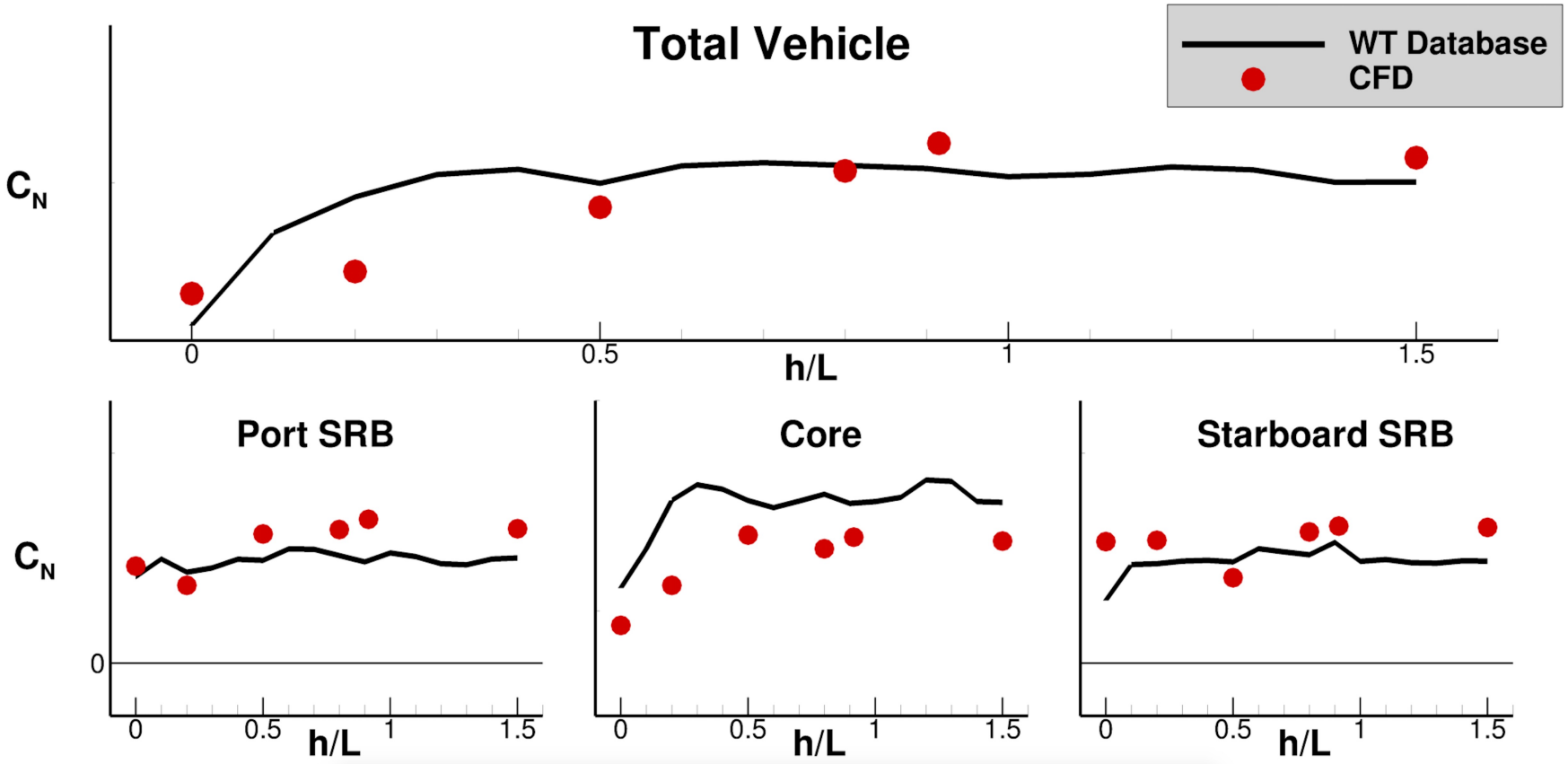
TUNNEL (SYMBOL) VS. CFD (LINE) SURFACE C_P



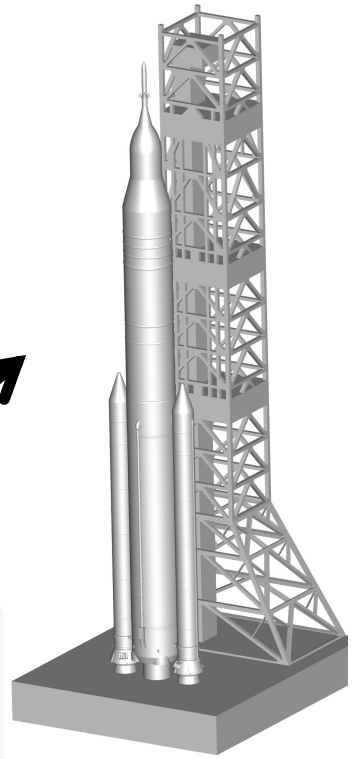
BLOCK 1B CREW IN PROXIMITY OF TOWER; Φ=180°



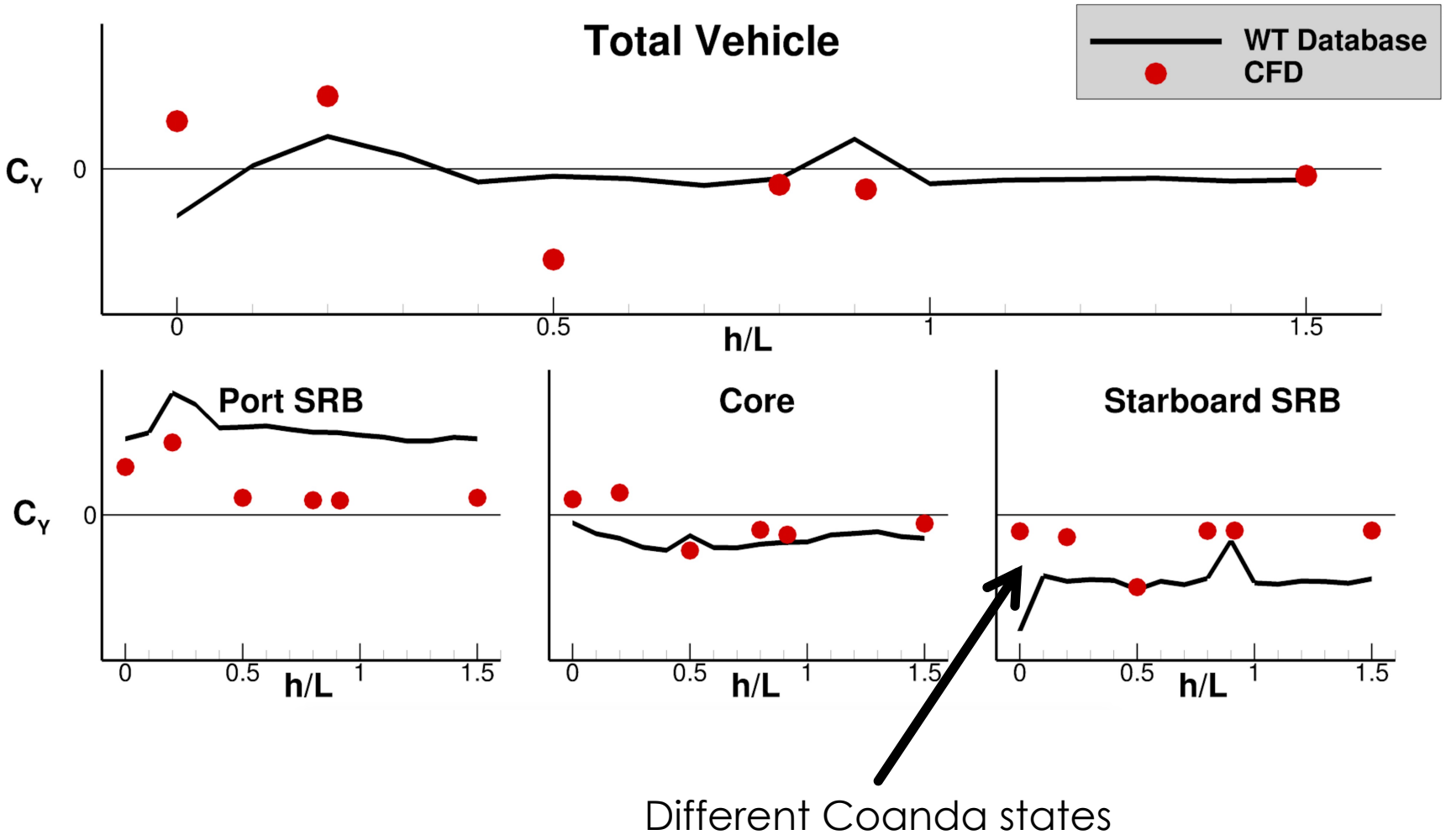
Freestream Flow



BLOCK 1B CREW IN PROXIMITY OF TOWER; Φ=180°



Freestream Flow



Different Coanda states

OUTLINE

- **Introduction and Overview**
- **Methods**
- **Liftoff and Transition Above Tower**
- **Liftoff and Transition in Proximity of Tower**
- **Other Program Requests**
  - Atmospheric Boundary Layer
  - Emergency Egress
  - Mobile Launcher Platforms
  - Thermal Protection System Repair
  - Uncertainty Quantification

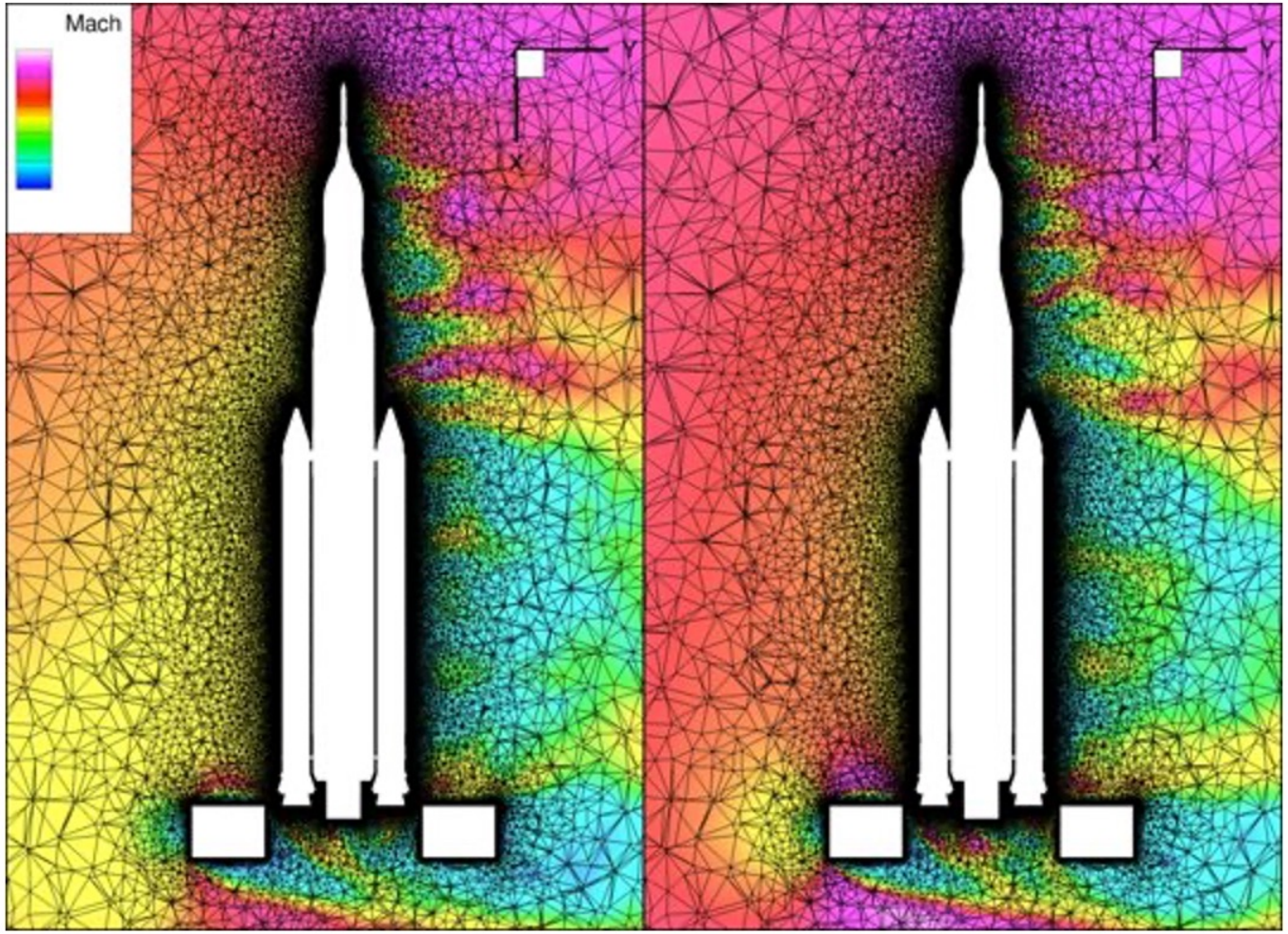


ARTEMIS PROGRAM SUPPORT

- **Numerous requests from SLS, Exploration Ground Systems, and Orion**
  - Effect of atmospheric boundary layer
  - Loading on the Launch Abort System access hatch
  - Aerodynamics of the Crew Access Arm
  - Analyses for Mobile Launcher Platforms
- **Nuanced database development**
  - Carefully crafted test matrix developed to capture complexities of flow behavior rather than a simple rectangular matrix
  - The structure of the standard database requires alteration for some cases
  - Example: deliver databases with multiple Coanda or asymmetric vortex states

ATMOSPHERIC BOUNDARY LAYER

- **Atmospheric boundary layer yields different conditions along tower**
  - Boundary layer can be hundreds of feet tall
  - Baseline analysis routines do not include an atmospheric boundary layer
- **Differences to lineloads quantified and incorporated in database**
- **Informs uncertainty of the Ground Force Loads databases**

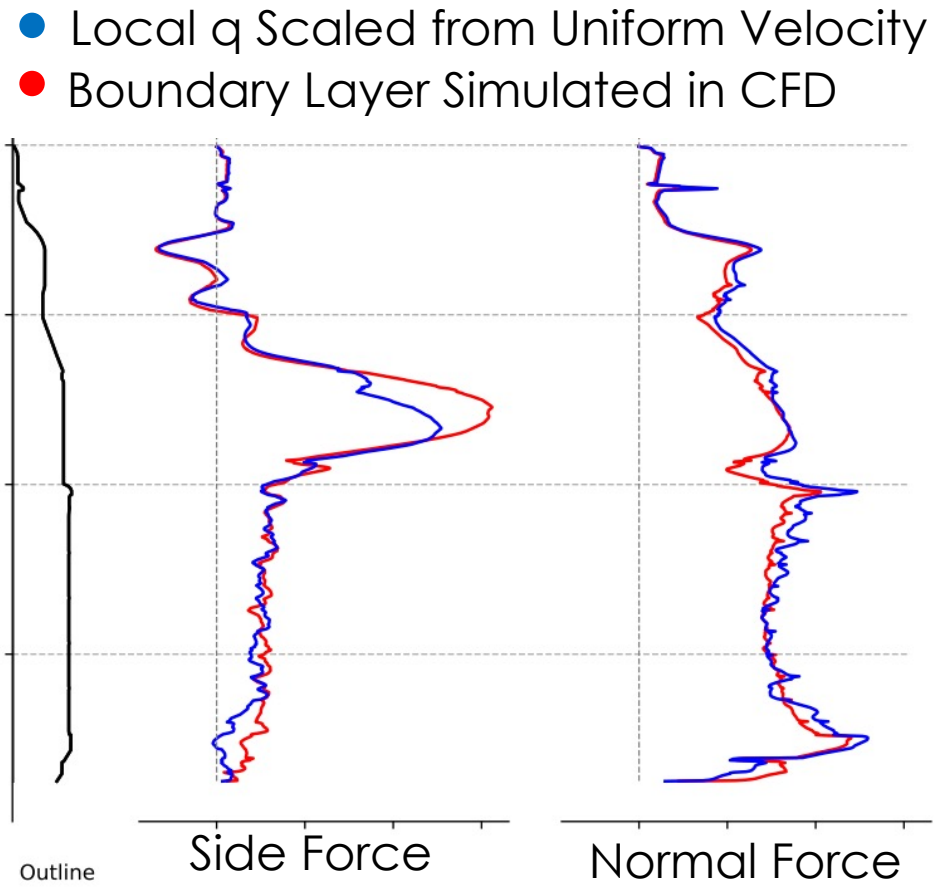


With Atmospheric Boundary Layer

No profile

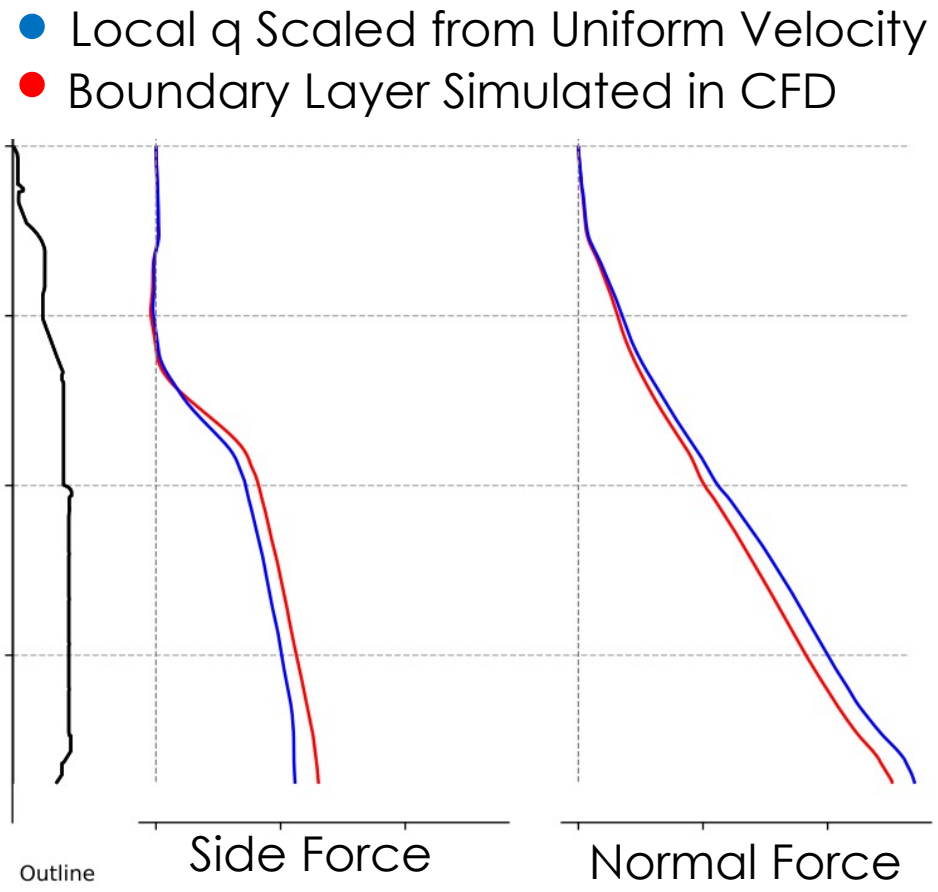
ATMOSPHERIC BOUNDARY LAYER

- **Uniform inflow assumption is not fully accurate for real-world analysis**
  - Determination of dimensional loads requires local q scaling of sectional coefficients
  - Can only be prescribed along a Cartesian axis in Kestrel
  - Would require many different grids for a range of roll angles
- **Analysis in Kestrel scales sectional forces by global q**
- **Largest differences in sectional forces seen near SRB noses**



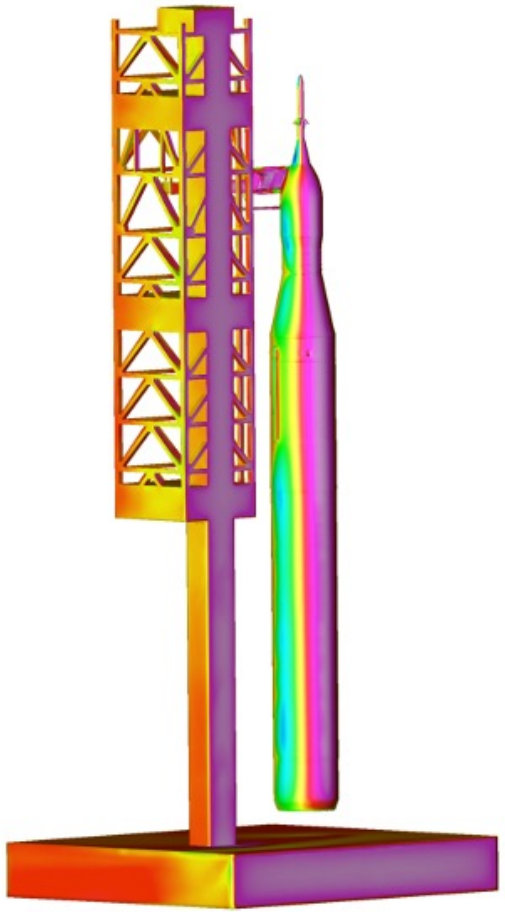
ATMOSPHERIC BOUNDARY LAYER

- **Uniform inflow assumption is not fully accurate for real-world analysis**
  - Determination of dimensional loads requires local q scaling of sectional coefficients
  - Can only be prescribed along a Cartesian axis in Kestrel
  - Would require many different grids for a range of roll angles
- **Analysis in Kestrel scales sectional forces by global q**
- **Largest differences in sectional forces seen near SRB noses**
- **Cumulative forces accentuate differences**
  - Forces integrated from forward point
  - Yield ~10% difference in total forces



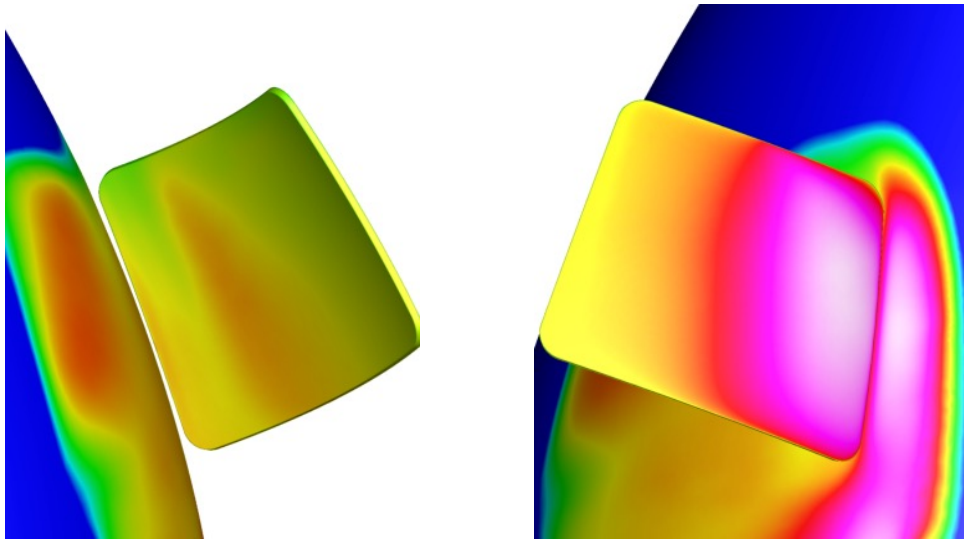
ORION LAS HATCH

- **Fairly exhaustive computational study**
  - Database of 36 cases over four weeks
  - Simplified tower geometry with a high-fidelity Crew Access Arm
  - Computational approach with subcomponent formulation deemed sufficiently accurate
- **Crew Access Arm retracted two hours before launch**
- **Key program conclusions**
  - Hatch loads increase with decreasing hatch angle which decreased the maximum allowable day-of-launch wind speed
  - CAA load database used to ensure the hydraulic systems are sized appropriately (must be within 45 sec.)



EMERGENCY EGRESS OVERVIEW

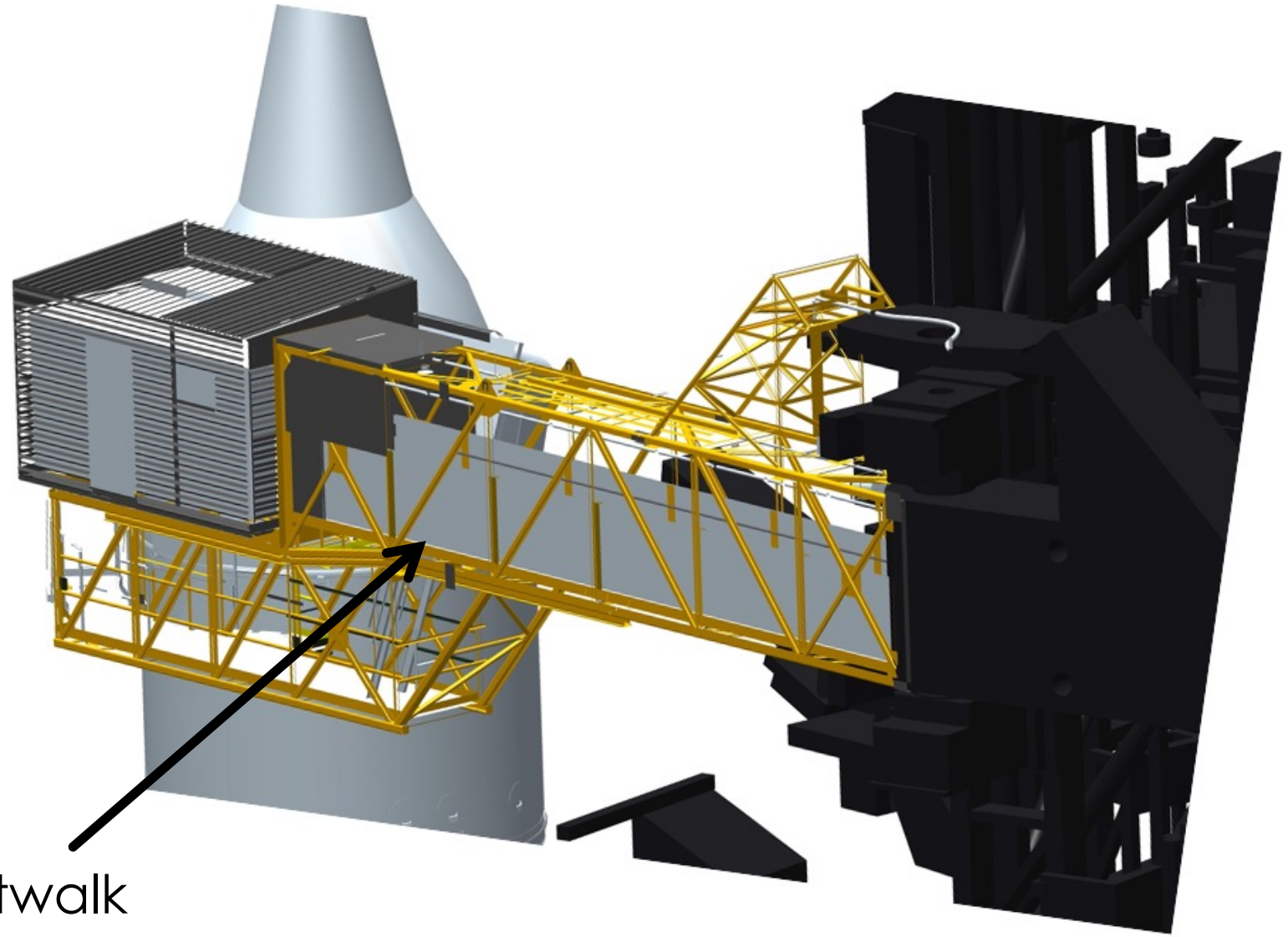
- **Ensuring safe astronaut emergency egress requires aerodynamic understanding of key subcomponents**
  - Launch Abort System escape hatch
  - Crew Access Arm
- **Data are of particular interest on the Launch Abort System escape hatch and the Crew Access Arm**



SURFACE MODELING – CAD

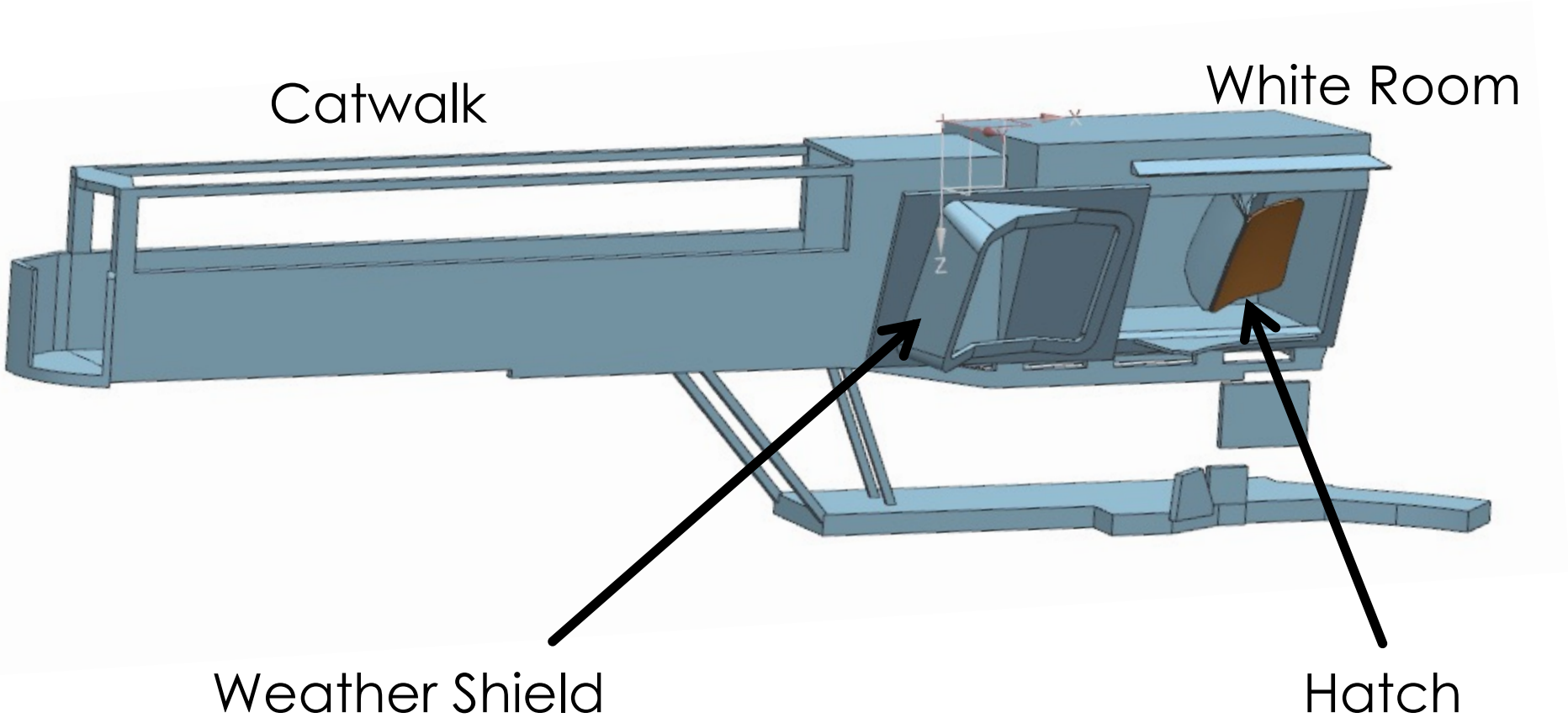
White Room

Open during emergency egress

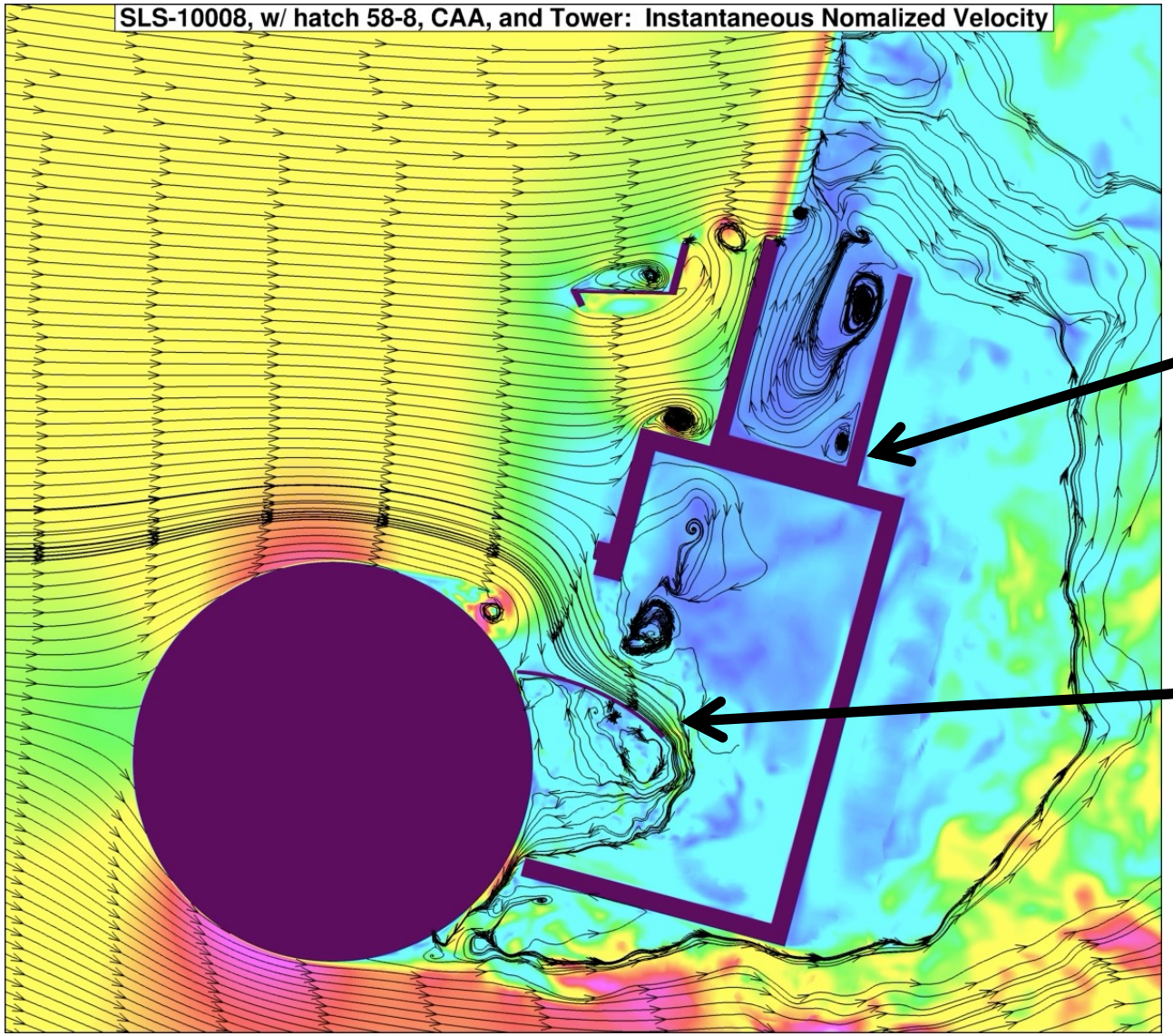


Catwalk

SURFACE MODELING – CFD



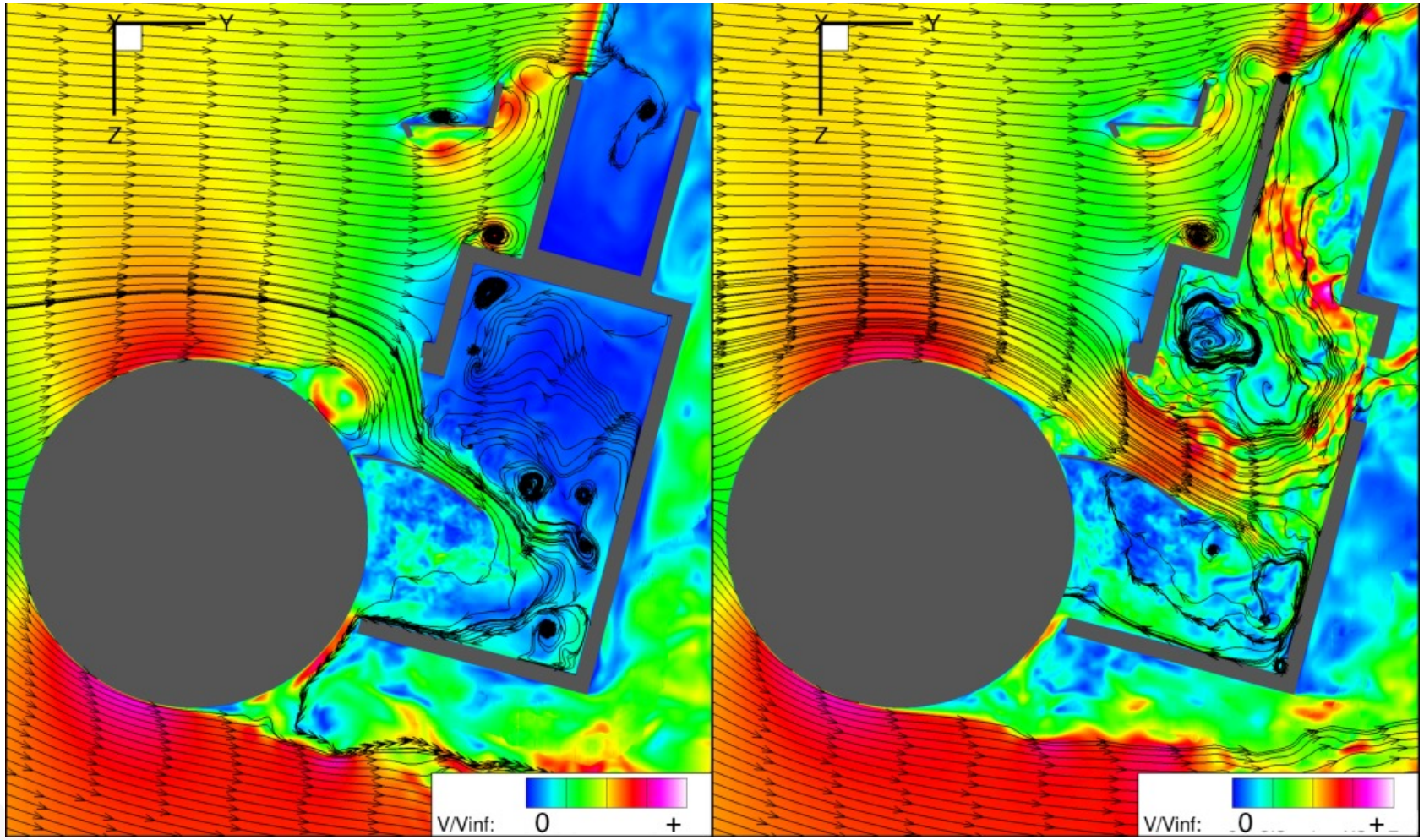
STREAMLINES WITH VELOCITY CONTOURS



STREAMLINES WITH VELOCITY CONTOURS

White Room Closed

White Room Open



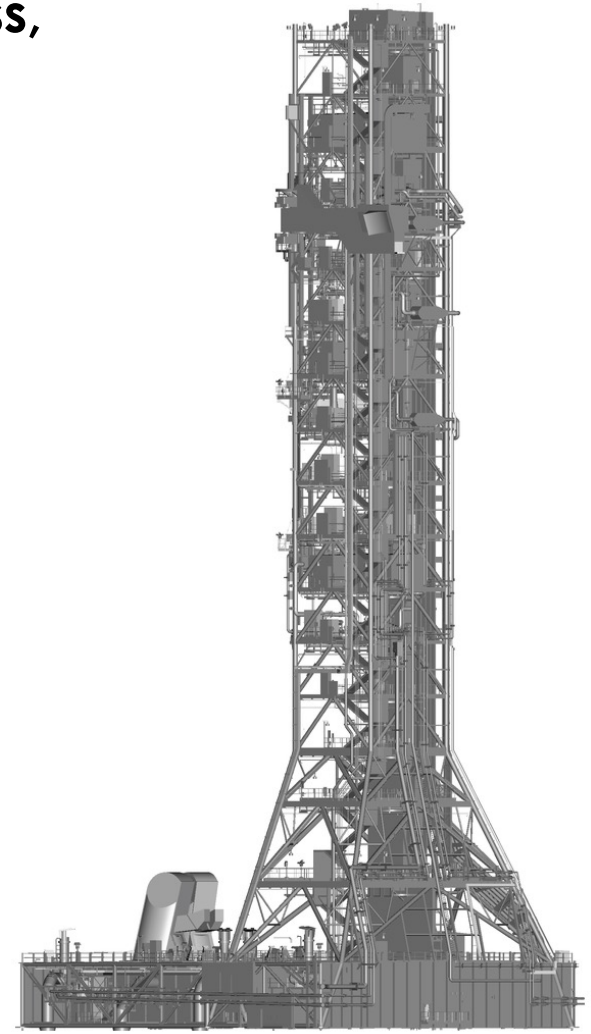
MOBILE LAUNCHER

- **Mobile Launcher used to assemble, process, transport, and launch the SLS vehicle**

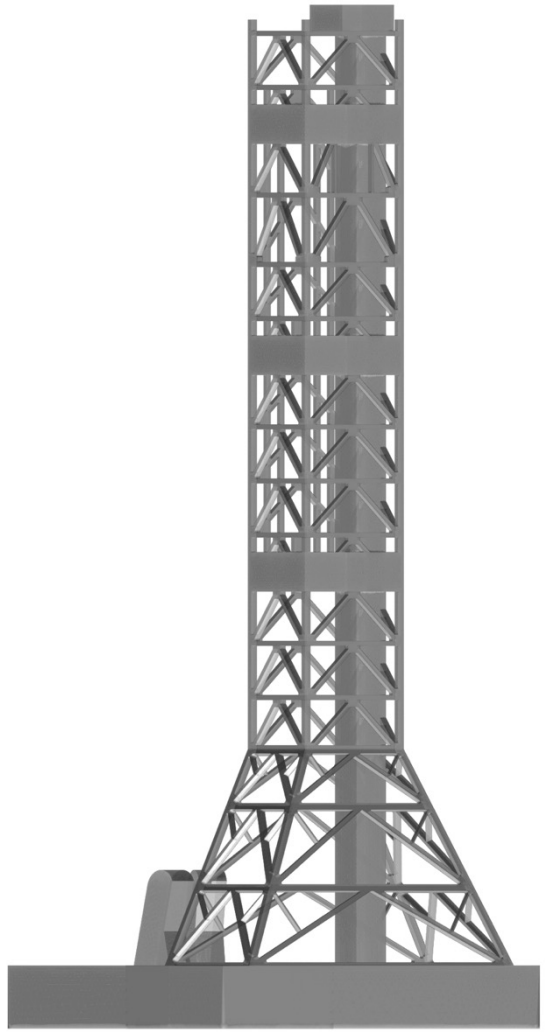


MOBILE LAUNCHER

- **Mobile Launcher used to assemble, process, transport, and launch the SLS vehicle**
- **Many simplifications made relative to production CAD with key features retained**



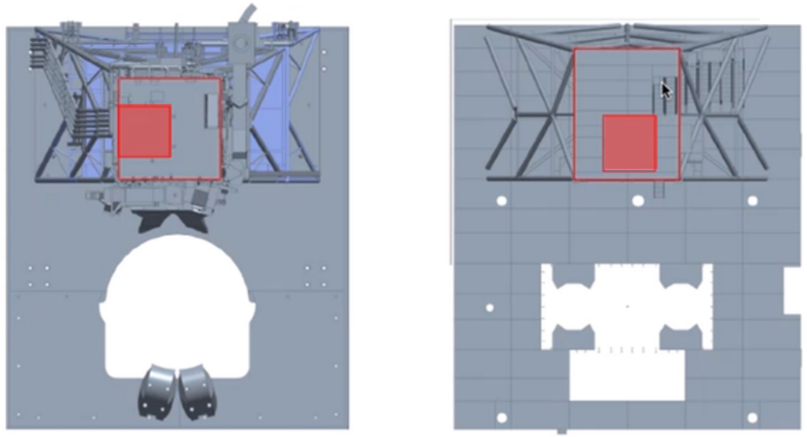
Recent ML CAD



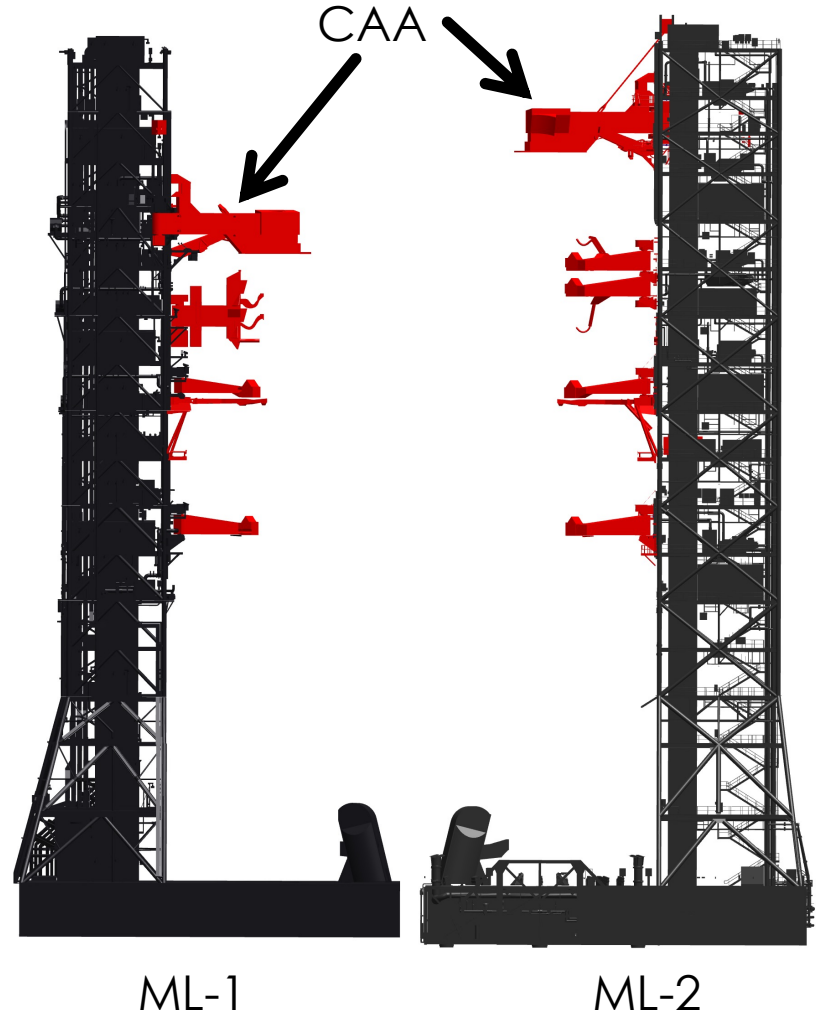
CFD Geometry

MOBILE LAUNCHER

- **Mobile Launcher used to assemble, process, transport, and launch the SLS vehicle**
- **Many simplifications made relative to production CAD with key features retained**
- **Rocket mounted on a base, supported by a tower, which moves to the launch pad**
  - ML-1 used for Block 1
  - ML-2 used for Block 1B and Block 2



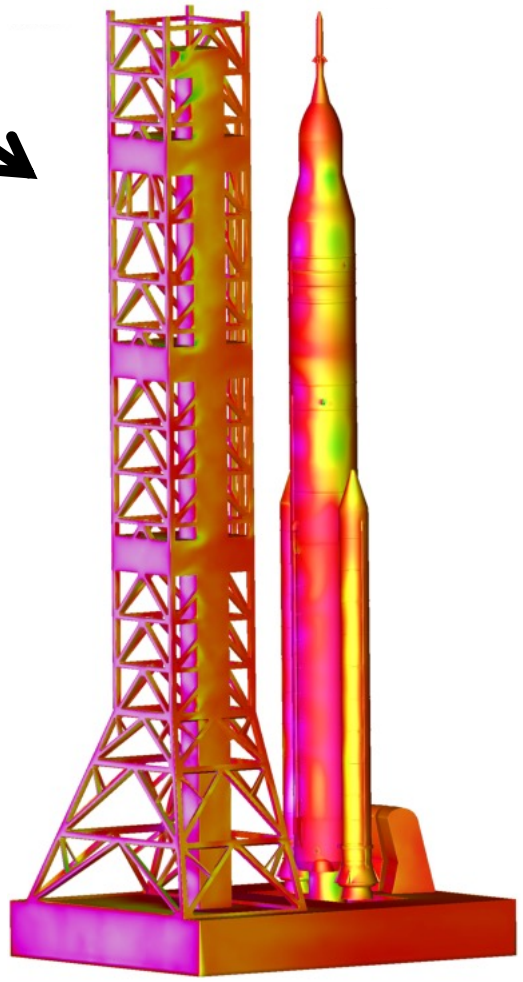
ML-1 ML-2



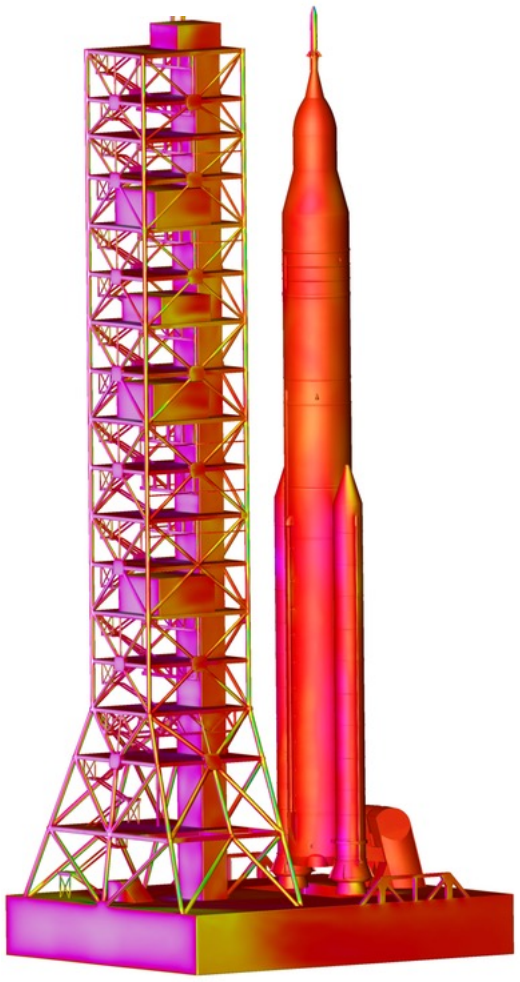
ML-1 ML-2

ML-1EX AND ML-2 COMPARISON

Flow Direction

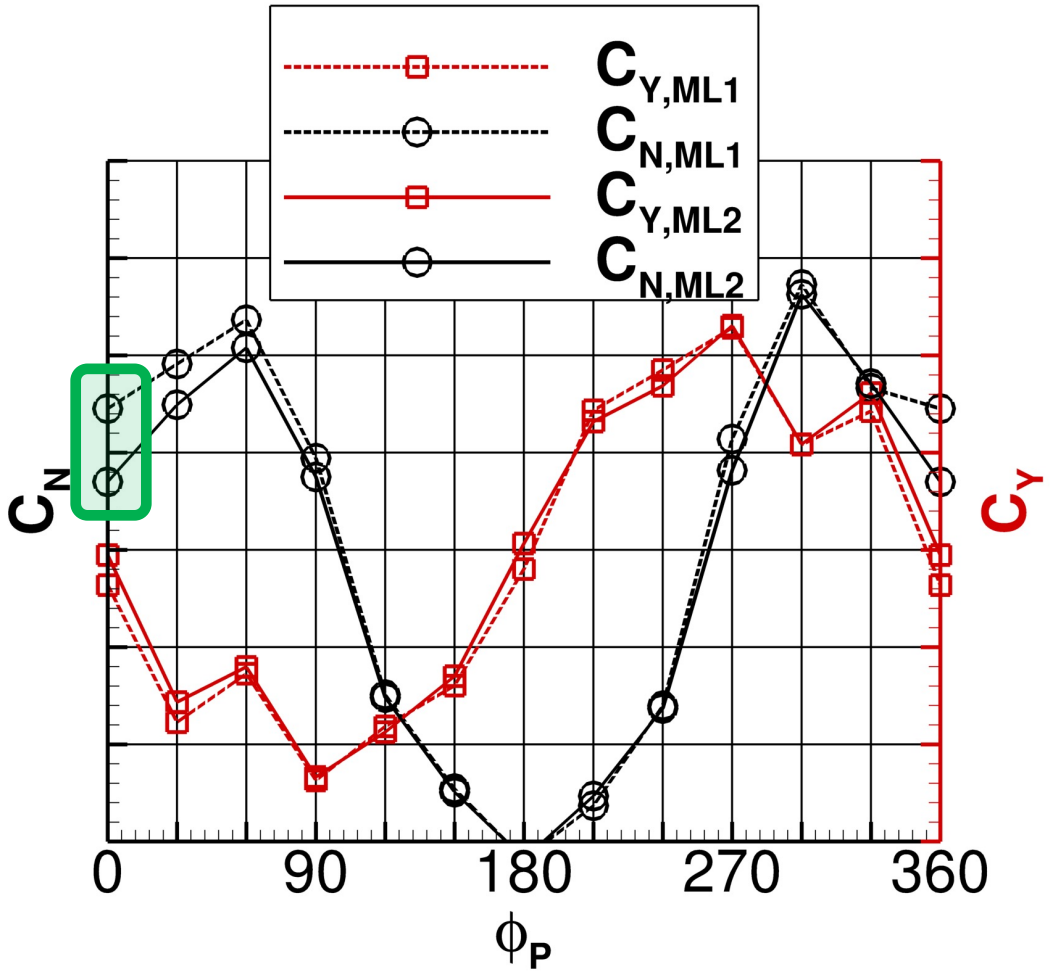


ML-1ex



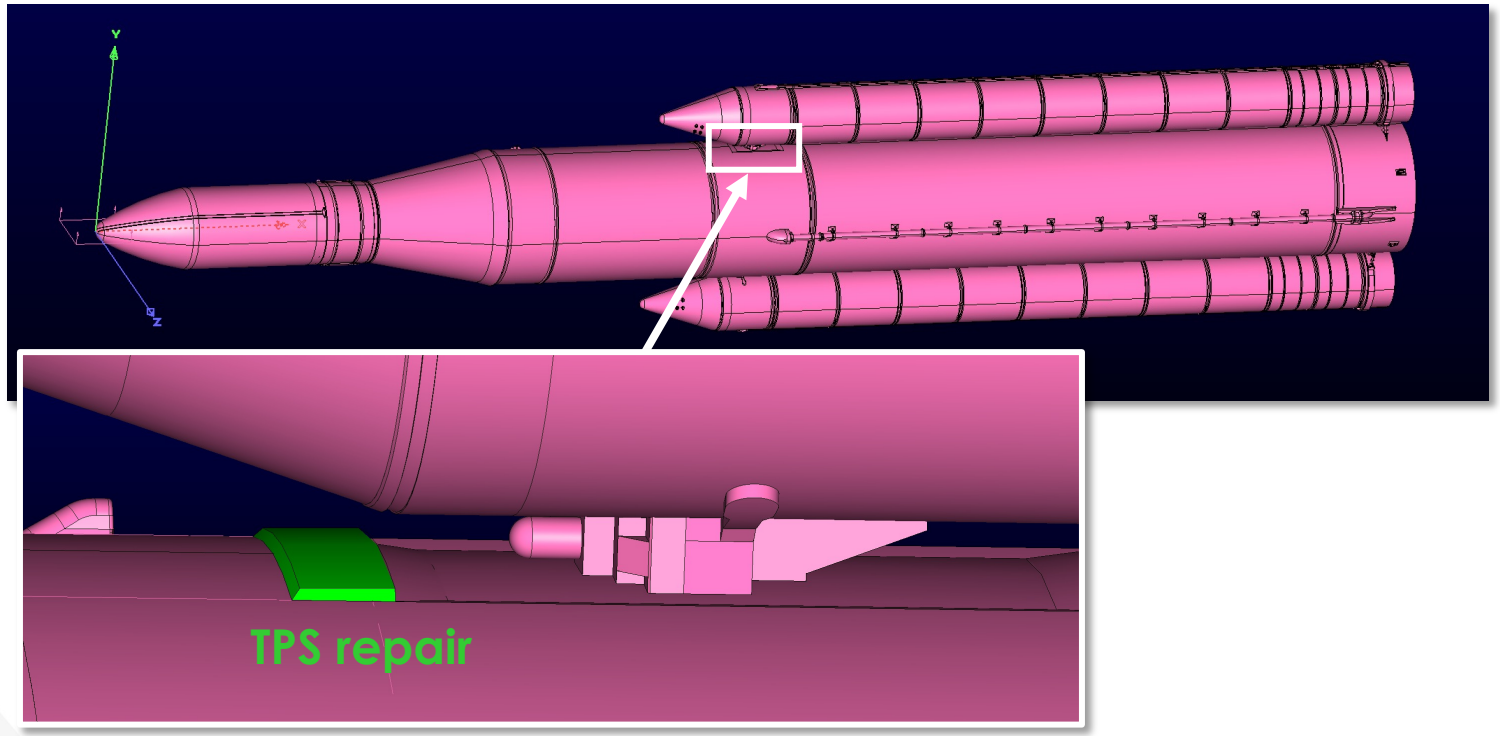
ML-2

ML-1 AND ML-2 COMPARISON



THERMAL PROTECTION SYSTEM (TPS)

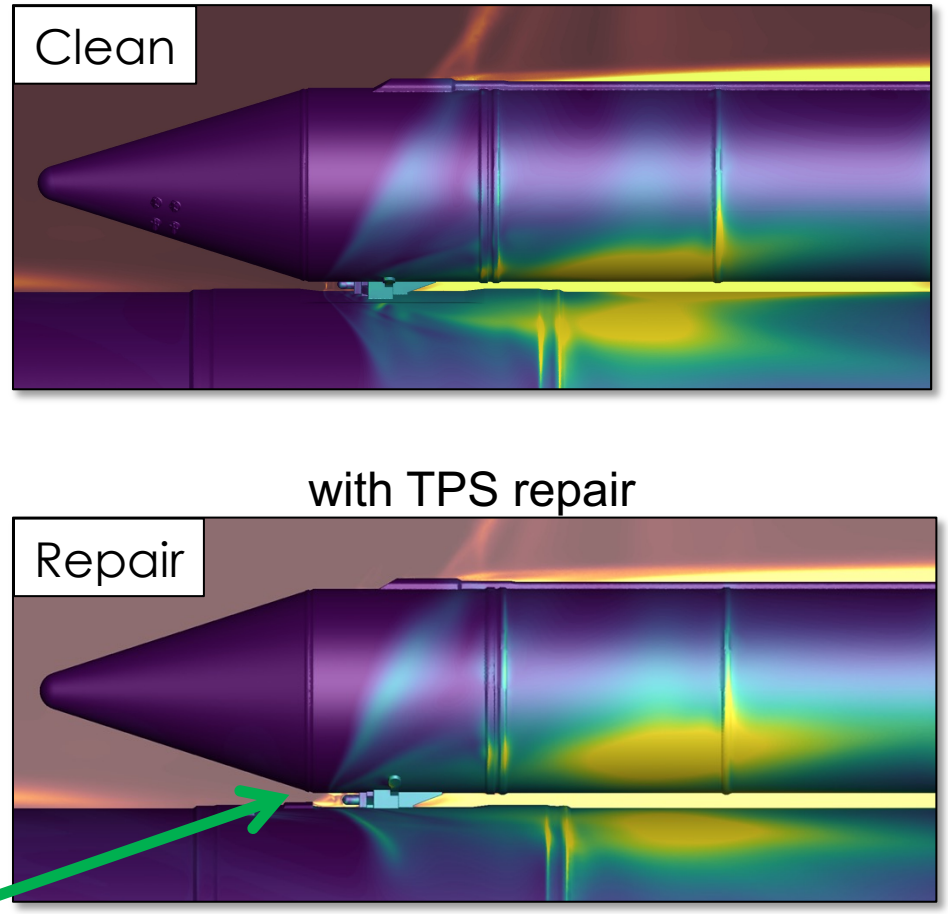
- Repair to thermal protection system on SLS core needed due to Green Run handling
- Program requested buffet and aeroacoustic analysis within ten weeks
- Large-scale time-accurate simulations compared clean vs repaired OMLs



THERMAL PROTECTION SYSTEM (TPS)

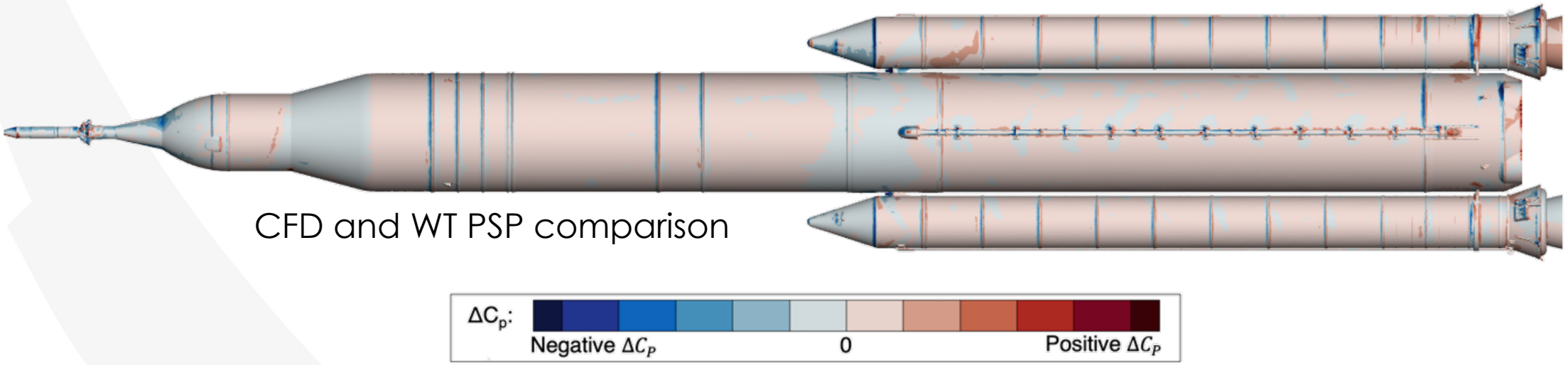
- **Extraordinarily expensive simulations**
  - 400,000 iterations on GPUs
  - Equivalent of 14,400 Skylake nodes (or 576,000 processors)
  - ~30 days to run
- **Complex analysis required small time step and fine grid**
  - Inadequate resolution yields excessive energy in large-scale structures
  - Calculated on 450m cells (baseline simulations ~80-200m cells)
  - Resolves 8kHz sampling rate
- **Small differences in forces are within typical uncertainty bands**

Contours of fluctuating-pressure RMS



CFD AND UNCERTAINTY QUANTIFICATION

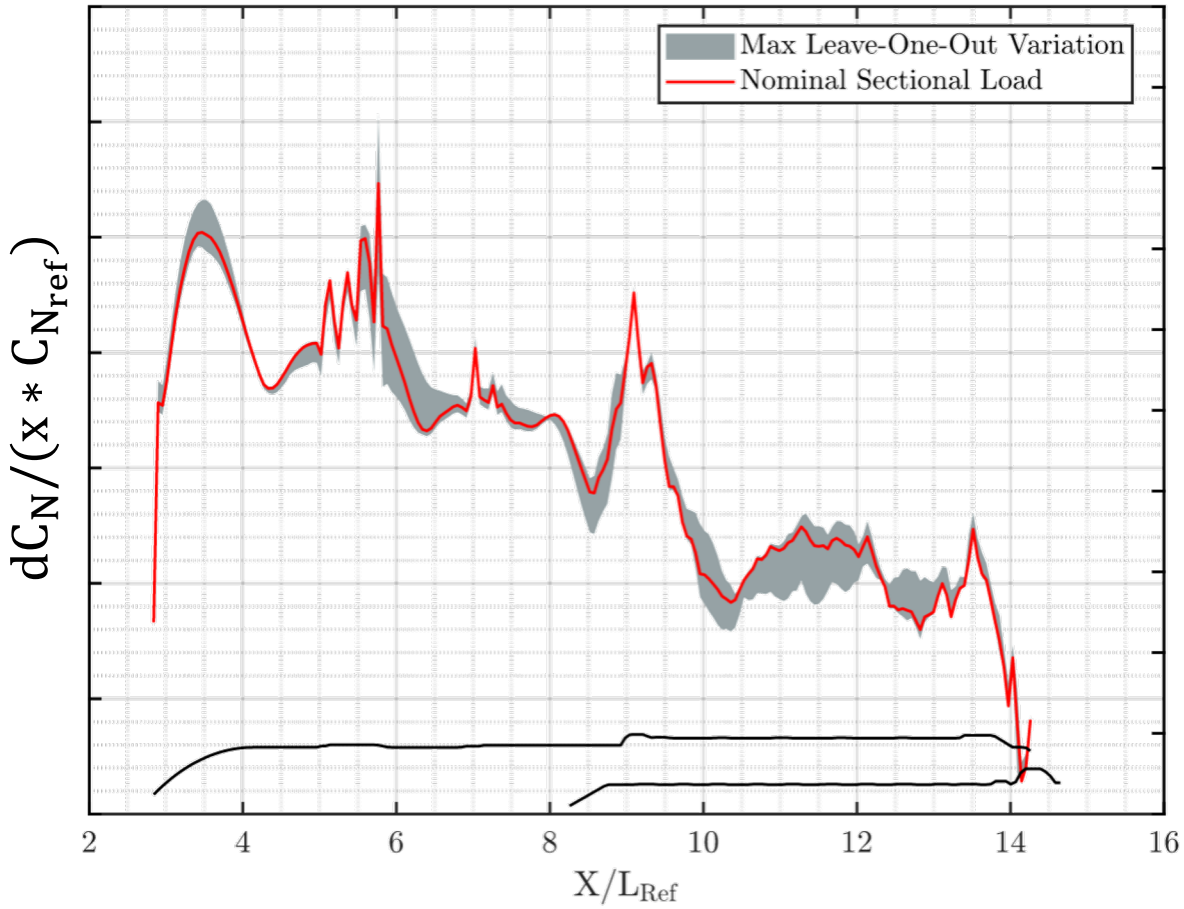
- **Code-to-code comparisons**
  - Kestrel, USM3D, and FUN3D
  - Same geometry, same conditions, different codes
- **Code-to-tunnel comparisons**
  - "Replicating" wind tunnel tests
  - Very similar geometry, comparable (rarely identical) conditions
- **Database model verification**
  - Use test points to characterize interpolation fidelity of databases



CFD and WT PSP comparison

CFD AND UNCERTAINTY QUANTIFICATION

- **CFD uncertainty has not yet been fully quantified**
- **Technology development underway**
  - Leave-one-out residuals
  - Time-dependent lineloads
  - Data fusion reduced-order models

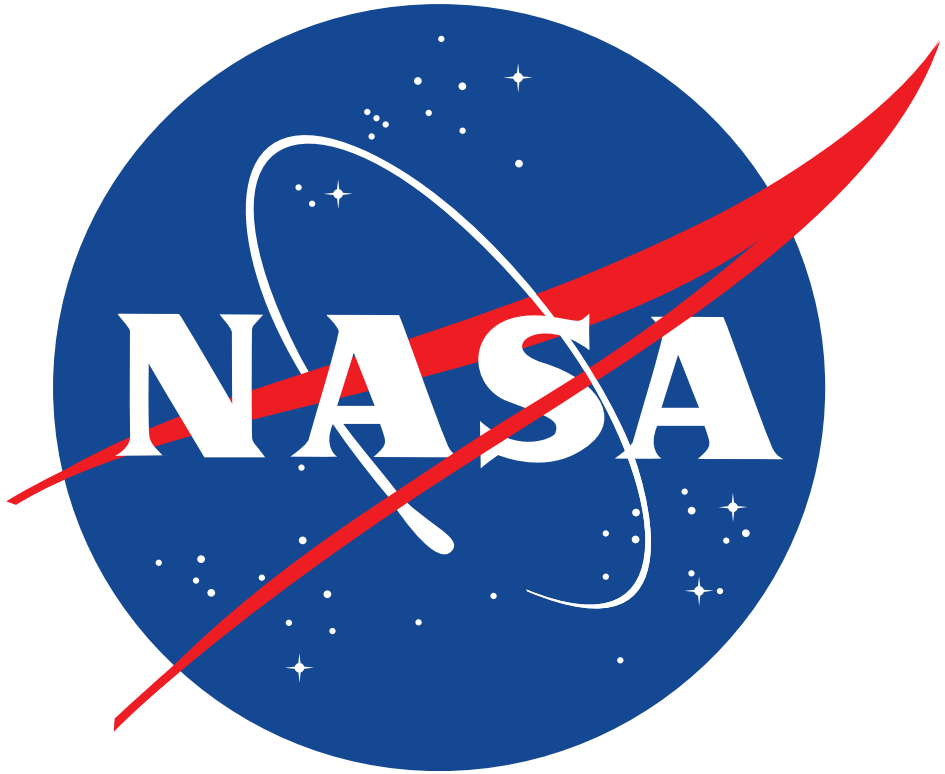


SUMMARY

- **Extensive efforts have been undertaken to evaluate low-speed SLS aerodynamics**
  - Flight regimes include prelaunch, liftoff and transition
  - First ~20 sec. of flight with days on the launch pad
  - Includes effects of the tower and isolated vehicle
- **Methods have been developed and refined while establishing best practices**
  - Separated flow requires DDES (or higher) to achieve desired accuracy
  - Isolated vehicle databases can be developed using CFD and supplemented by models
  - Computational analysis in the presence of the tower is challenging



QUESTIONS?



brent.w.pomeroy@nasa.gov

PUBLISHED REFERENCES

Krist, S., "Results from DES Simulations of an SLS Variant at Liftoff Conditions with Comparison to Experiment," AIAA Paper 2015-0776, AIAA Aerospace Sciences Meeting, Kissimmee, FL, 2015.

Ratnayake, N., "Selection of Computational Tools Used in Development of the Space Launch System Liftoff and Transition Lineloads Databases," AIAA Paper 2019-1840, AIAA SCITECH Forum, San Diego, CA, 2019.

Krist, S., "Kestrel Results at Liftoff Conditions for a Space Launch System Configuration in Proximity to Launch Tower," AIAA Paper 2019-3400, AIAA SCITECH Forum, San Diego, CA, 2019.

Wignall, T.J., "Liftoff and Transition Database Generation for Launch Vehicles Using Data-Fusion-Based Modeling," AIAA Paper 2019-3401, AIAA SCITECH Forum, San Diego, CA, 2019.

Ratnayake, N., "Kestrel Results at Liftoff Conditions for a Space Launch System Configuration in Proximity to the Launch Tower," AIAA Paper 2019-1841, AIAA AVIATION Forum, Dallas, TX, 2019.

Ratnayake, N., "Computational Fluid Dynamics Methods Used in the Development of Space Launch System Liftoff and Transition Lineloads Databases," AIAA Paper 2019-3399, AIAA AVIATION Forum, Dallas, TX, 2019

Ratnayake, N., "Unstructured Grid Development for the Space Launch System Liftoff and Transition Lineloads Computational Analysis," AIAA Paper 2020-0672, AIAA SCITECH Forum, Orlando, FL, 2020.

Wignall, T.J., "Uncertainty Quantification for Launch Vehicle Aerodynamic Lineloads," AIAA Paper 2020-1521, AIAA SCITECH Forum, Orlando, FL, 2020.

Pomeroy, B., "Validation of Kestrel IDDES Simulations for SLS Transition Analysis," AIAA Paper 2022-1335, AIAA SCITECH Forum, San Diego, CA and Virtual, 2022.

Walker, M., "Cross-Validation of Computational and Experimental Distributed Surface Pressures on the Space Launch System," AIAA Paper 2022-0431, AIAA SCITECH Forum, San Diego, CA and virtual, 2022.

Pomeroy, B., "Verification and Validation of the Kestrel Solver for Space Launch System Low-Speed Aerodynamic Analysis," NASA Technical Publication, in review, 2022.

Upcoming: 2023 SCITECH Special Sessions